Files are in Adobe Acrobat 3.0 format.

5th Annual Joint Aerospace Weapon System Support, Sensors and Simulation Symposium, San Diego, CA

13-18 June 99

Table of Contents

"Prognostics Framework" by Dr. Li Pi Su, Redstone Arsenal, US Army

"IEEE Information Modeling Standards for Test and Diagnosis" by Dr. John Sheppard, ARINC and Mr. Mark Kaufman, NWAS
"Automatic Detection of Radar Signature Defects" by Ms. Nancy Cheadle, Modern Technology Solutions, Inc.

"Tunable, Narrowband Filter for LWIR Hyperspectral Imaging" by Mr. Andrew Bodkin, Ion Optics, Inc.

Thursday, June 17

"Radar Signal/Image Processing Enhancements Using Alpha-Stable Techniques" by Dr. Roger Lee, Naval Air Warfare Center

"3D Signature Visualization of Air Vehicles" by Mr. Robert C. Hicks, Jr., Modern Technology Solutions, Inc.

"Electronic Distribution of Technical Information (EDTIS) via Satellite" by Mr. Charles P. Satterthwaite, US Air Force, AFRL/IFTA

"Smoke and Obscurant Modeling in Support of Simulation-Based Acquisition and Training" by Mr. David J. Johnston, OptiMetrics, Inc.

"Improved Fidelity for Calculating Attenuation Through Obscurants" by Ms. Scarlett D. Ayres, White Sands Missile Range, US Army

"Silent Sentry - Passive Surveillance" by Ms. Lorraine Martin, Lockheed Martin

JAWS S3 Panel I
Requirements Generation for Total Battlespace Awareness

Mr. Allen Murashige
Directorate of Command & Control
HQ USAF/XOC

15 June 1999

Challenges in a Changing Defense Environment

- Fundamental Changes
-
- Three Major Challenges
-
- Adapting to Change, Meeting the Challenges

Fundamental Changes

- Information Revolution
- Revolution in Military Affairs
- Dynamic Post-Cold War Strategic Environment
-
-
- *How do we adapt?*
- *How do we stay ahead of the competition?*

Three Major Challenges

DIRECTORATE OF COMMAND & CONTROL

- How do we adapt to concurrently changing strategic environments, adversaries, missions, concepts, doctrine, organizations, systems, technologies?
- How do we create products for the warfighter which are not obsolescent when fielded?
- How do we balance the need for immediate, tailored, locally optimized solutions…

  against the desire for robust, enduring, globally capable solutions

Challenge #1: Adapting to Change

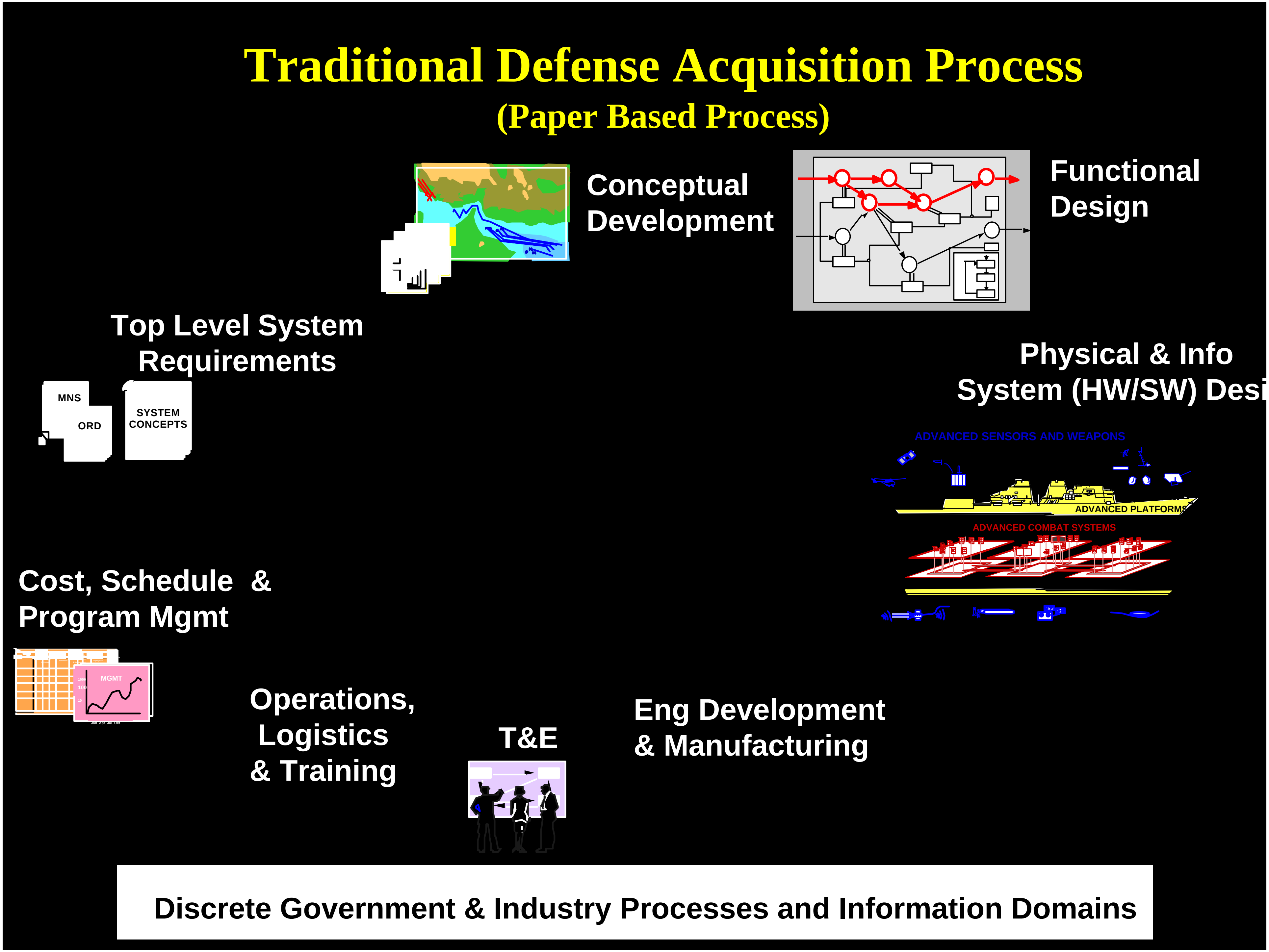
Approach

- Experimentation (near term)
  - Purpose: Push the edge of the envelope to expand our knowledge and understanding of emerging technologies, systems, and concepts
  - Encourage & reward exploration, innovation, risk taking
    - Expect, accept & learn from concept “failures”
  - Determine key parameters & measures
    - Improve our qualitative & quantitative understanding
    -
- Research (long term)
  - Encourage research in adaptive systems: evolutionary programming, genetic algorithms, neural nets

Challenge #2: Avoiding Obsolescence

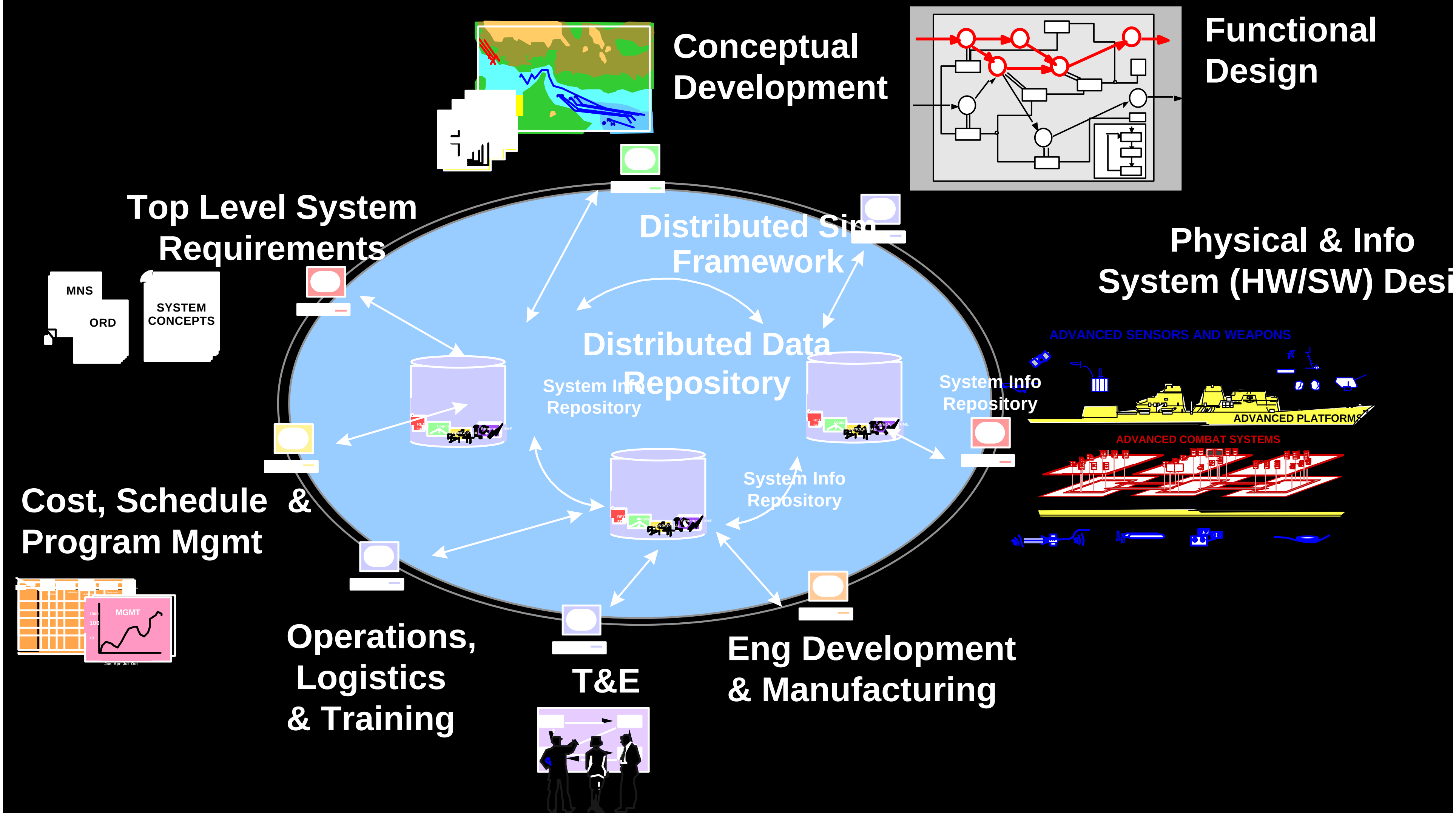
Approach: Simulation Based Acquisition

- Revamp acquisition process to capitalize on the advances, advantages & potential of digital information technology
-
- Use shared access to distributed information to:
  - Facilitate iterative, spiral development
  - Facilitate collaborative, concurrent processes
  - Create synergy between requirements pull & technology push


Traditional Defense Acquisition Process
(Paper Based Process)
Conceptual Development
Functional Design
Top Level System Requirements
MNS
ORD
SYSTEM CONCEPTS
Physical & Info System (HW/SW) Desi
ADVANCED SENSORS AND WEAPONS
ADVANCED PLATFORMS
ADVANCED COMBAT SYSTEMS
Cost, Schedule & Program Mgmt
MGMT
Operations, Logistics & Training
T&E
Eng Development & Manufacturing
Discrete Government & Industry Processes and Information Domains

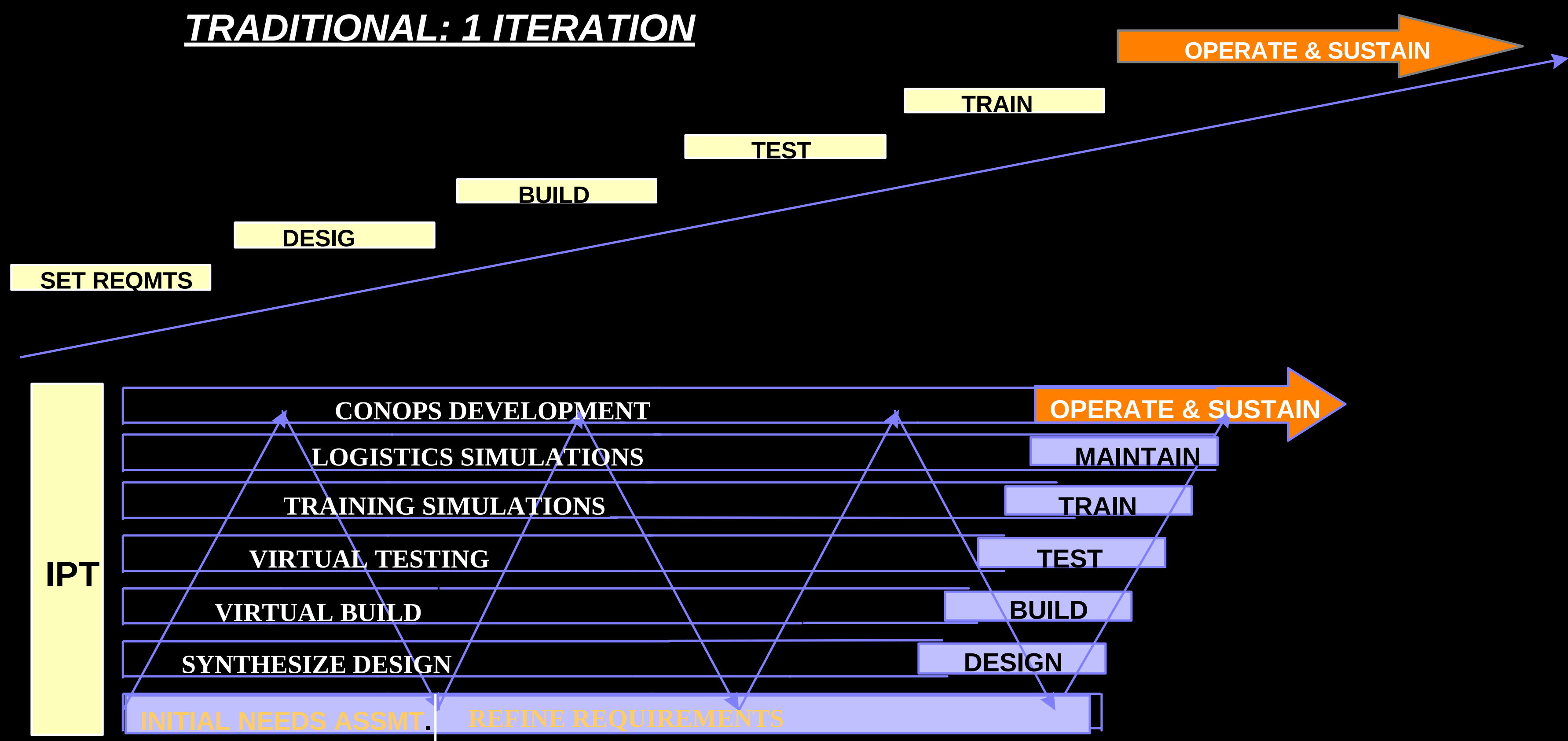
SBA Operational Concept Illustration

(Digital Information Based Process)



Extensive Re-use Across Phases and Across Acquisition Programs

SBA: Enabling Integrated & Iterative Processes



***SBA: MULTIPLE ITERATIONS** (MULTIPLE DESIGN LEARNING CYCLES)*

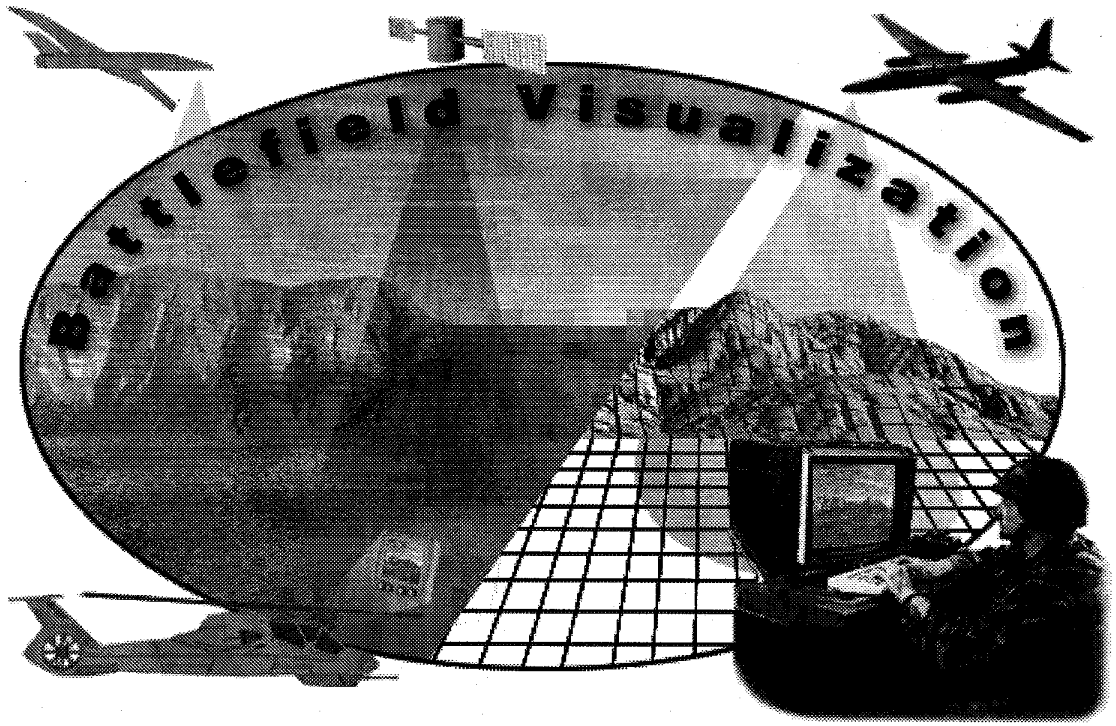
Challenge #3:
Local vs Global Solutions

Approach

- Develop & adhere to recognized architectures & standards
- Examples: JTA, DII-COE, HLA, JMASS, Database standards, etc
- Incentivize compliance
- Engage professional societies (eg, IEEE, AIAA) to encourage broad recognition & acceptance of architecture & standards
- Plan for growth: Service to Joint to Coalition, Government + NGO, Mil Spec to Commercial

Summary

- Highly dynamic defense environment, now and for the foreseeable future
- Three major challenges will not be easily solved
- Suggested approaches should help, but more will be needed
- Your ideas and support are solicited



BATTLEFIELD AWARENESS
UNDERSTANDING THE FULL REQUIREMENT

Paul Menoher
Lt Gen, US Army (Ret)

STERLING SOFTWARE

"Information is the currency of victory on the modern battlefield"

Gen Gordon Sullivan, Then CSA

The requirement is to get the <u>right information</u> to the <u>right people</u> at the <u>right time</u> and to <u>present</u> it in a manner that its <u>significance</u> and <u>implications</u> for your forces and missions <u>are immediately apparent and understood</u>.

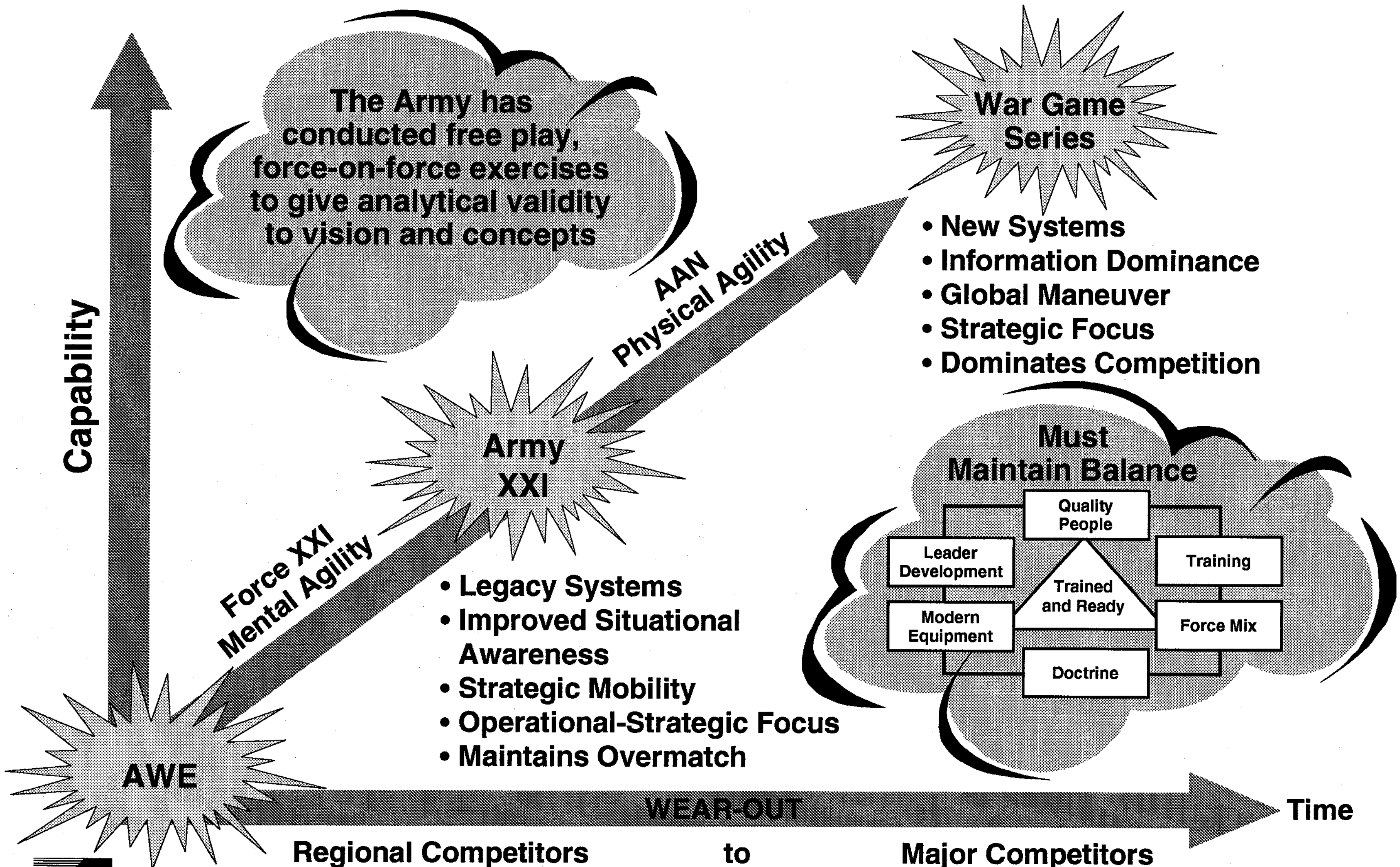
STERLING SOFTWARE

U.S. Army Requirements Process

- The U.S. Army has a Concept-Based Requirements System (CBRS) in which the intellectual process of developing an underpinning operational concept precedes the physical process of developing new systems. This intellectual process ensures you understand what you need and how it fits within your overall operational or warfighting schema. It addresses the following key factors:

D – Doctrine
T – Training
L – Leader Development
O – Organizational Implications
M – Materiel
S – Soldiers

The Path to AAN Begins with the Advanced Warfighting Experiments and Passes through Army XXI



STERLING SOFTWARE

Goal of Force XXI

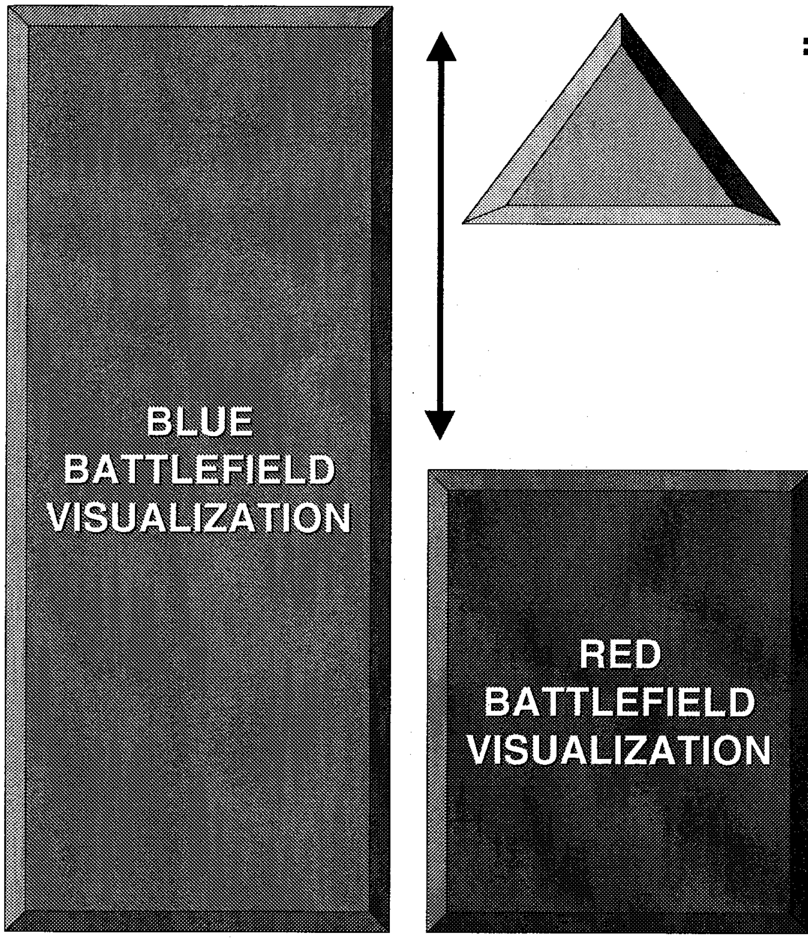
- To enable the US Army to advance into the 21st Century as a land combat force that is more lethal and survivable and can control the operations tempo in any future conflict through enhanced Battle Command and information dominance. It is capable of:
  - Simultaneous planning and execution of multiple operations;
  - Always maintaining the initiative; and
  - Forcing the enemy to operate from significant disadvantage or quit

Mental Agility

"The ability to leverage information dominance and enhanced Battle Command to act and react significantly faster than your opponent based on a clear and current understanding of the battlespace and the enemy – to keep the enemy always at risk and preclude him from responding effectively."

Menoher, '98

Information Dominance



= **Information Dominance**

- The aggregate of Information Operations activities that create an **advantage**
- Not just in the **amount** of information but in the relative capacity for **Battlefield Visualization**
- The Commander's **understanding** of his **current state** in relation to the **enemy** and the **environment**… **and**…his ability to see these in the context of a **desired end state**… **and**…his ability to visualize the **sequence of activity** that will move his force from its current state to its desired end state

Battle Command

- The art of decision-making, leading and motivating soldiers and their organization into action to accomplish missions. *It includes visualizing the current state and desired future state, then formulating the concept of operation to get from one to the other at least cost.*

  (FM 100-5, Jun 93, and TRADOC PAM 525-5, Aug 94)

Changing Nature of Battle Command

BEFORE	DIGITIZED
■ Vertical	■ Integrated
■ Hierarchical	■ Collaborative
■ Sequential	■ Concurrent/NRT

Multi-Dimensional Attacks Across the Battlefield

In Stride Mission Changes

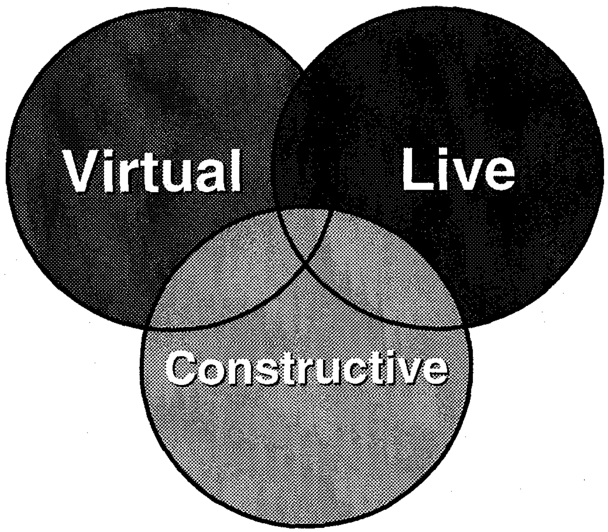
Command on the Move

Battlefield Visualization

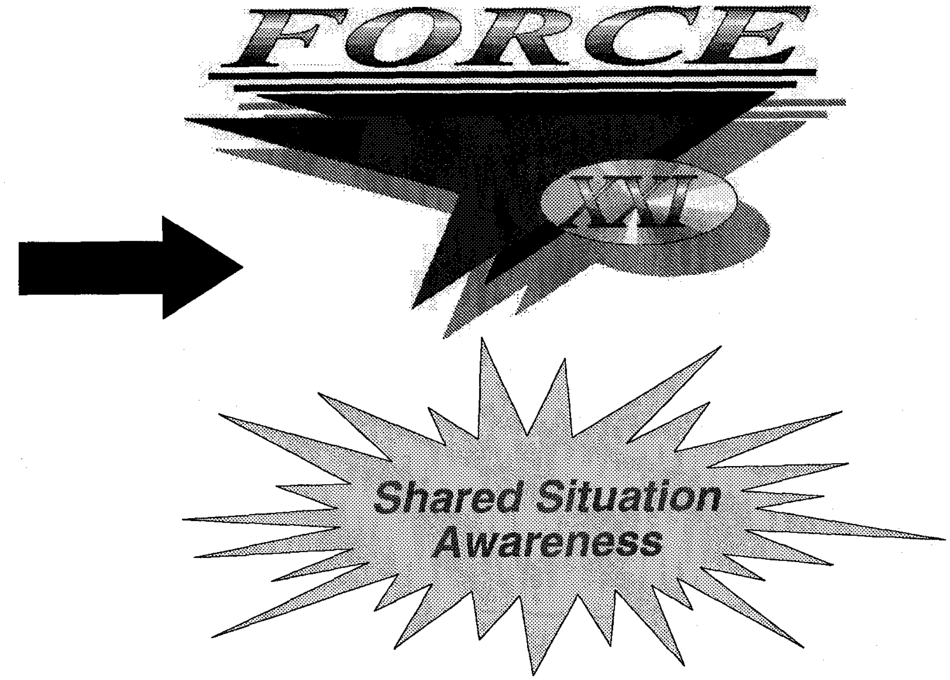
- "The process whereby the commander develops a clear understanding of his current state with relationship to the enemy and the environment, envisions a desired end state, and then subsequently visualizes the sequence of events that will move his force from the current state to the desired end state."

  (TRADOC PAM 525-70, Oct 95)

Battlefield Visualization
Our Objective



Today



Drive Live, Virtual and Constructive environments into one coherent architecture for America's Army, using the Army Technical Architecture as our guide

One system to train for, plan, wargame, rehearse, and execute operations

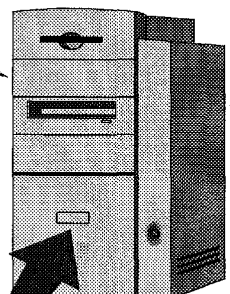
Major Issues

- Requirement for high resolution DTED
- Interoperability and integration of non-, partially, and differently digitized units
- Leader development
- Perishable skills
- Requirement for synthetic training environments to develop, then maintain, requisite skill levels for leaders and operators

Battlefield Visualization
Enabling Technologies

Displays

Computer Hardware



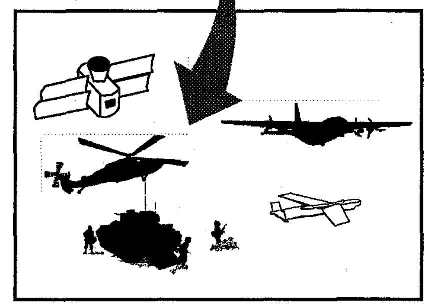
Software

- AI Collection Management
- WAN Info Retrieval & Processing
- Knowledge Tools

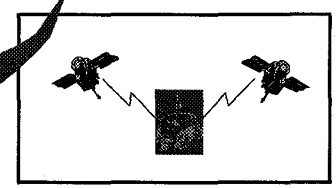
Visualization Databases

- Terrain
  - Elevation DB
  - Features DB
  - Texture DB
  - Images DB
- Synthetic Environments
- Dynamic
  - Entities
  - Units
  - Terrain
  - Environment

Automatic Target Recognition

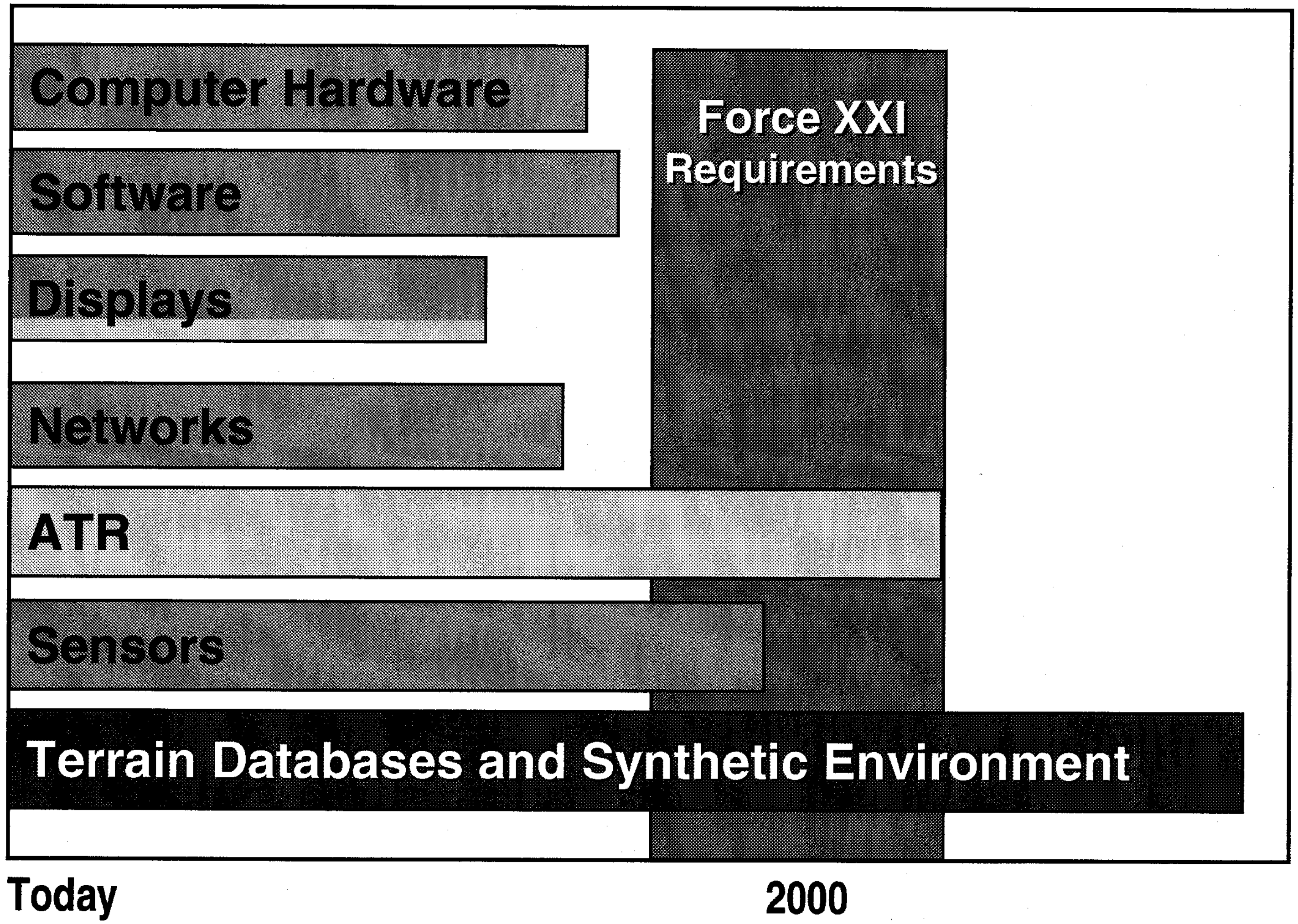


Sensors



Networks

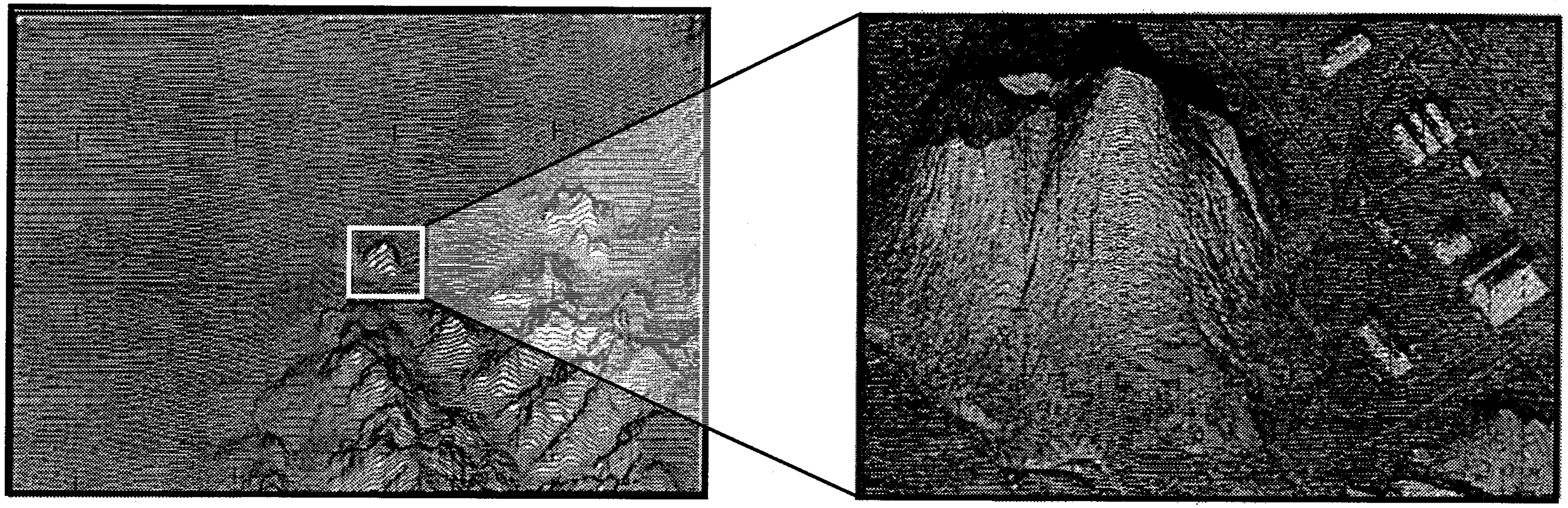
Technology Maturation
Support to Battlefield Visualization



Digital Terrain Data

Two Problems: Resolution & Coverage

DTED Level 1 (100 meter) | **DTED Level 4 (3 meter)**



- **Planning-level data (world-wide)**
  Levels 1 (100m) and 2 (30m)

  ↓ ↓

- **Coverage 66% < 3%**

- **Operation-specific areas require higher resolution data**
  Levels 3 (10m), 4 (3m), and 5 (1m)

  ↓

- **Virtually Nonexistent**

Uses for Hi-Res DTED

FUNCTION	DTED 1	DTED 2	DTED 3	DTED 4	DTED 5
• Planning					
• IPB					
• Msn Rehearsal					
– J/G-Staff					
– S-Staff					
– Air (Nap of the Earth)					
– Vehicle (2m obstacle)					
– Soldier (1m survivability)					
• Targeting					

<u>The lower the echelon, the higher the required resolution</u>

Interoperability Issues

- Defense budgets and time will not permit fielding of digitized Battle Command and intelligence systems with the same level of technology to the entire force
- There will never be a steady state; change and evolution will be constant
- There will always be legacy systems
- There will always be units with the latest technology the Army can field (“Haves”) and units with varying degrees of less capable systems, if anything (“Have Nots”)

Challenge

- To find an affordable way to provide "Have Nots" with the minimum essential, interoperable, digitized Battle Command and intelligence systems to enable them to learn how to operate and leverage information age technology to achieve information dominance and mental agility

Leader Development Challenge

- Leaders must understand what digitized systems can and cannot do and learn to trust them and the information they provide
- They must also learn how to exploit enhanced situational awareness to recognize battlefield conditions and dynamically synchronize their combat power to exploit opportunities
- They must maintain focus through their commander's intent and CCIR

Meeting the Challenge

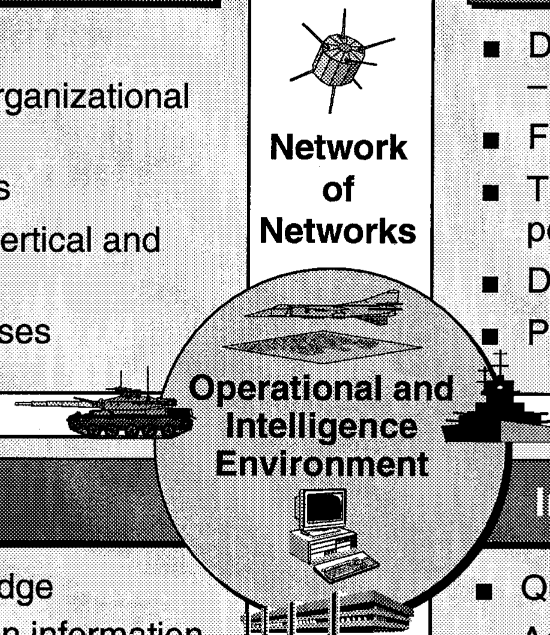
Understanding Decision Implications in the Information Age

Organizations

- Integration vice hierarchy
- Focus on functions vice organizational construct
- Teams vs. functional staffs
- Pervasive connectivity – vertical and horizontal
- Chaotic vice linear processes

Training and Doctrine

- Dynamic change in decision processes – mission rehearsal
- Full access to data
- Training support to a broader perspective
- Dynamic collaborative decision making
- Profound change (e.g. IPB and TTP)



Operations

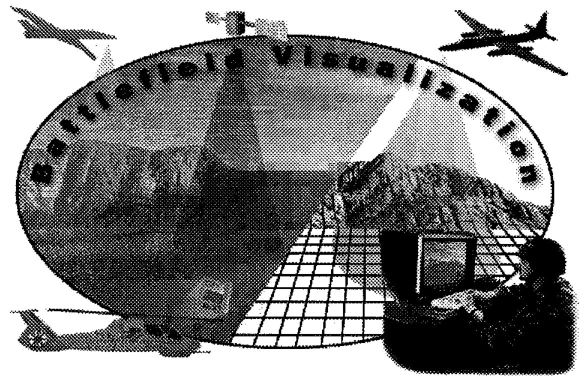
- Speed enabled by knowledge
- Broadened perspectives on information operations
- Multidimensional operations
- Profound NRT knowledge based
- New set of force protection challenges
- Focused analysis at point of decision

Info Mgmt/Tech Development

- Quality vs. quantity
- Accuracy and validation of knowledge
- Virtual headquarters seen as "real" entities
- "Machine-aided" decision…human confidence

Perishable Skills

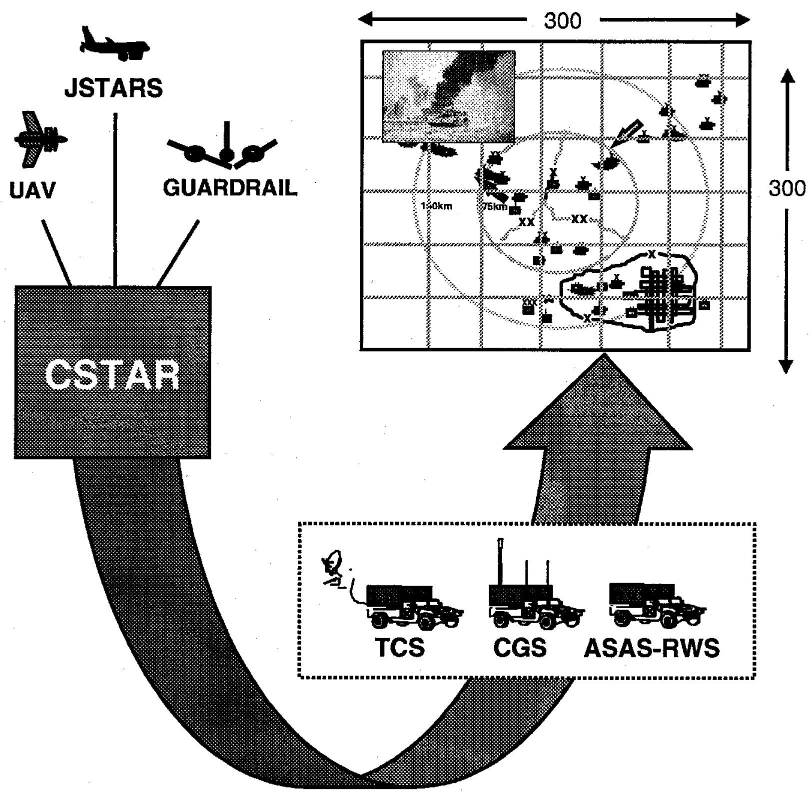
- Digital skills of leaders and operators are extremely perishable
- A "one time" pass through a training institution and/or a "Have" unit is not enough to maintain these skills
- We must develop high fidelity, synthetic training environments to support individual and collective training of these skills in garrison



Actions Being Taken

STERLING SOFTWARE

Synthetic Training Environment

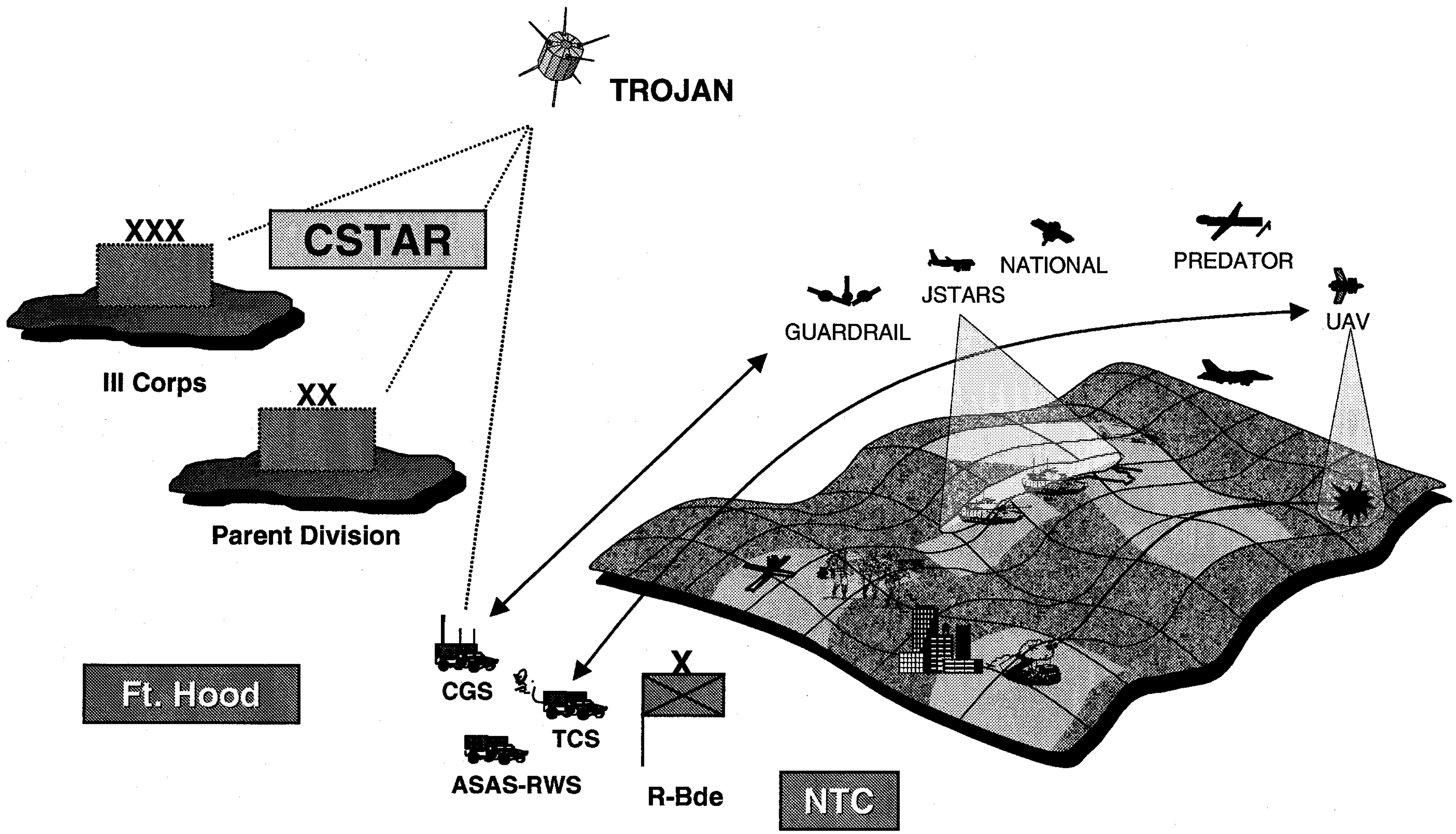


Combat Synthetic Training Assessment Range (CSTAR) – Phase I

- Merges live play and constructive simulation into coherent 300 x 300 km virtual scenario
  - Employs realistic collection models
  - Supplements or supplants scarce sensors
- Enables battle command training
  - Responsive to commander directions
  - Fuels fires and maneuver integration
- Supports new equipment fielding
  - CGS, TCS, ASAS-RWS

STERLING SOFTWARE

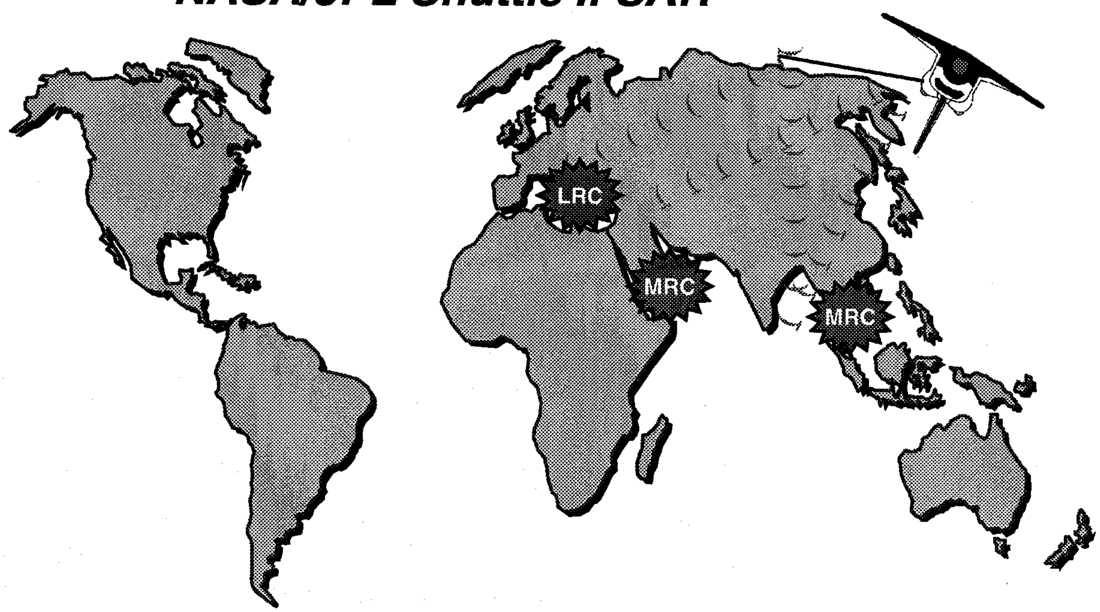
NTC – Ft Hood (Phase 1)



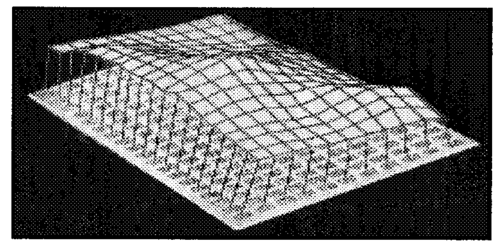
STERLING SOFTWARE

Digital Terrain Elevation Data

NASA/JPL Shuttle IFSAR



The Shuttle Can Provide DTED Level 2 Coverage of 80% of the World's Surface, *In A Single Mission*



- JROC-Approved; PBD Approved; Shuttle Flies in '00, Data in '01
- DTED Is a Significant Shortfall--Not Currently Available In the Resolution or Timelines Required by the Warfighter
- DTED Level 2 Data (30M Post Spacings) Will Provide a Robust Standardized Database for Mission Planning and Crisis Response
- An Enabling Technology for Battlefield Visualization

DTED Level 4, 5 (3m and 1m Post Spacings) Required for Operations

Rapid Terrain Visualization
ACTD Components

Rapid Terrain Visualization (RTVIZ) ATD
JPSD

TERRAIN COMPONENT

Battlespace Command and Control (BC2) ATD
CECOM

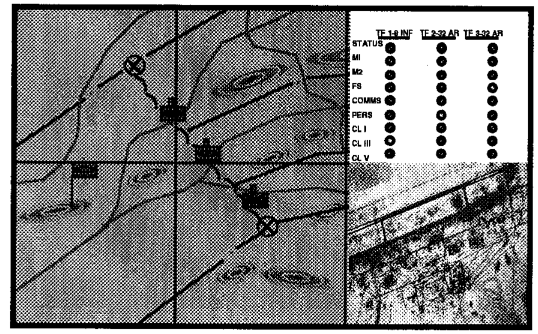
C2 / VISUALIZATION TECHNOLOGIES COMPONENTS

Red and Blue Data Integration

ARL Visualization Technology

Rapid T.V. ACTD JPSD

Commander Monitors the Battle
Movement to Contact "On Track"



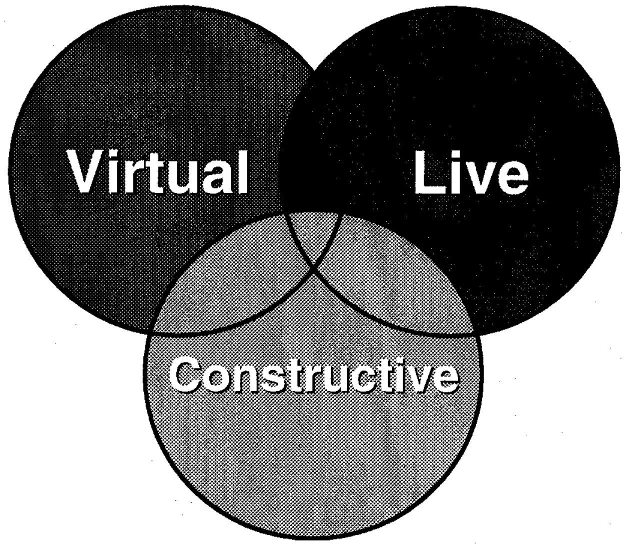
Users XVIII ABN Corps & EXFOR

Goal: To rapidly collect and generate high resolution terrain data in time to support force projection operations and to integrate current situational data and mission planning and rehearsal capabilities.

Value Added

- Merge ATCCS inputs in a single platform, output to large screen displays where appropriate or individual private displays for commanders on the move!
- Move battlestaffs (S/G/J) into the 21st century…"yellow stickie" wargaming on paper maps replaced by competitive force engagement in 3D on high resolution, virtual replication of the battlespace…artificial intelligence aided analysis…*objectivity replaces subjectivity*
- Enable every commander to see his battlespace, the array of friendly and enemy forces on it, and to plan, wargame and rehearse before ever making contact with the enemy
- Reduced uncertainty–replace subjectivity with objectivity, *across all BOS*

Battlefield Visualization
Our Objective



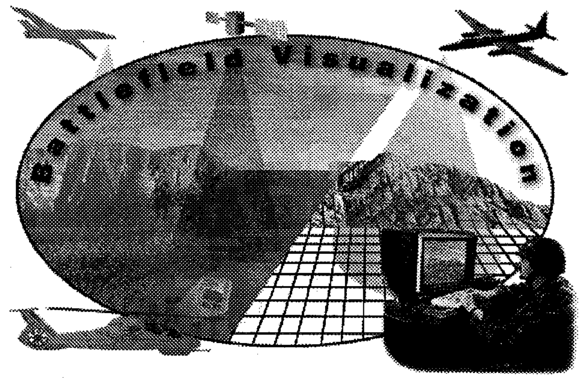
Today

Drive Live, Virtual and Constructive environments into one coherent architecture for America's Army, using the Army Technical Architecture as our guide

One system to train for, plan, wargame, rehearse, and execute operations

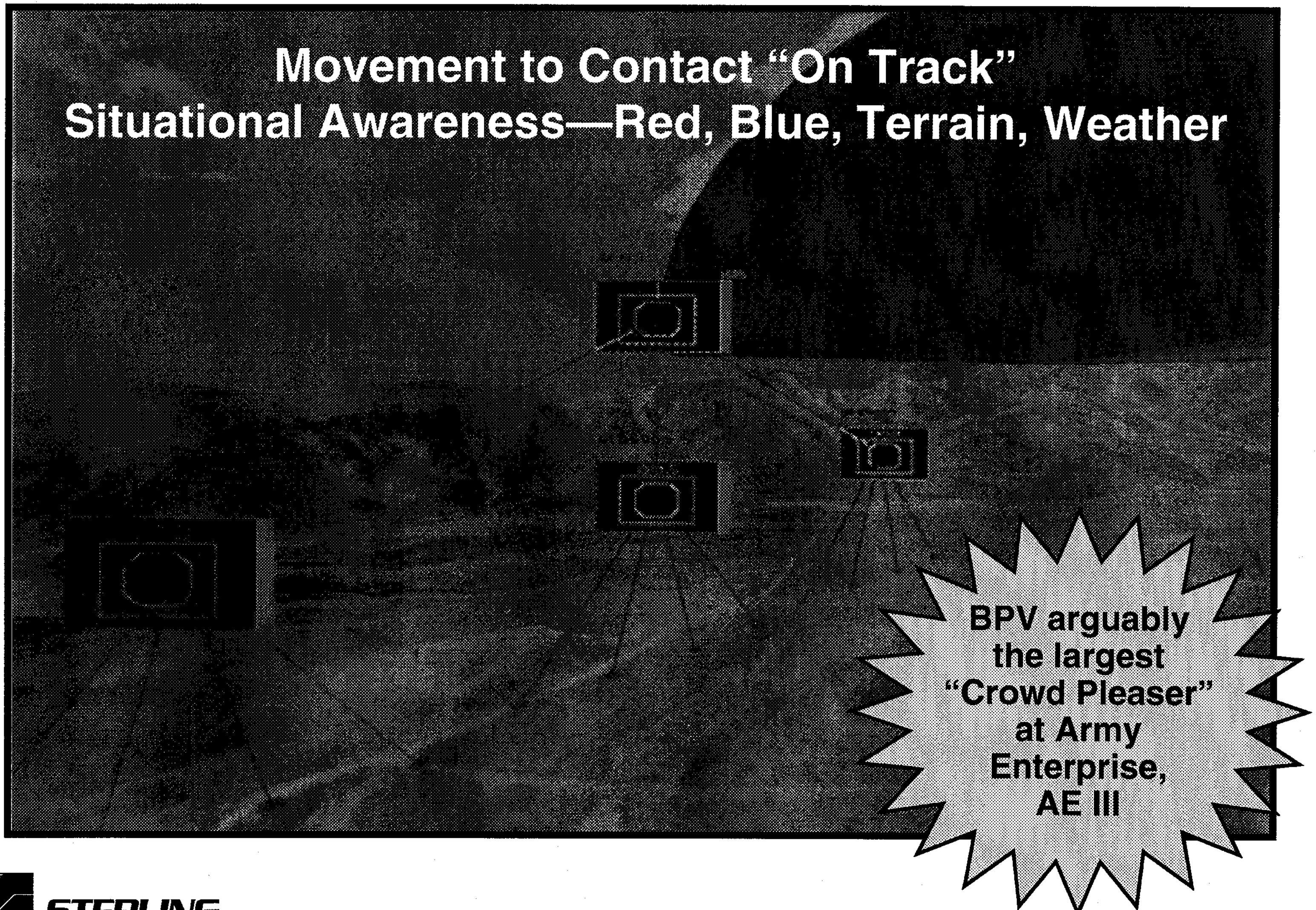
Conclusion

- Digitization and enhanced Battlefield Awareness stand to bring about many advances in Battle Command and overall warfighting capabilities
- However, integrating and optimizing digitization and fully leveraging battle awareness are complex tasks encompassing many more challenges than simply acquiring new systems
- There is much more involved in articulating requirements than merely writing system specifications or introducing new technologies
- Thinking through the DTLOMS provides a good start to understanding the full requirement

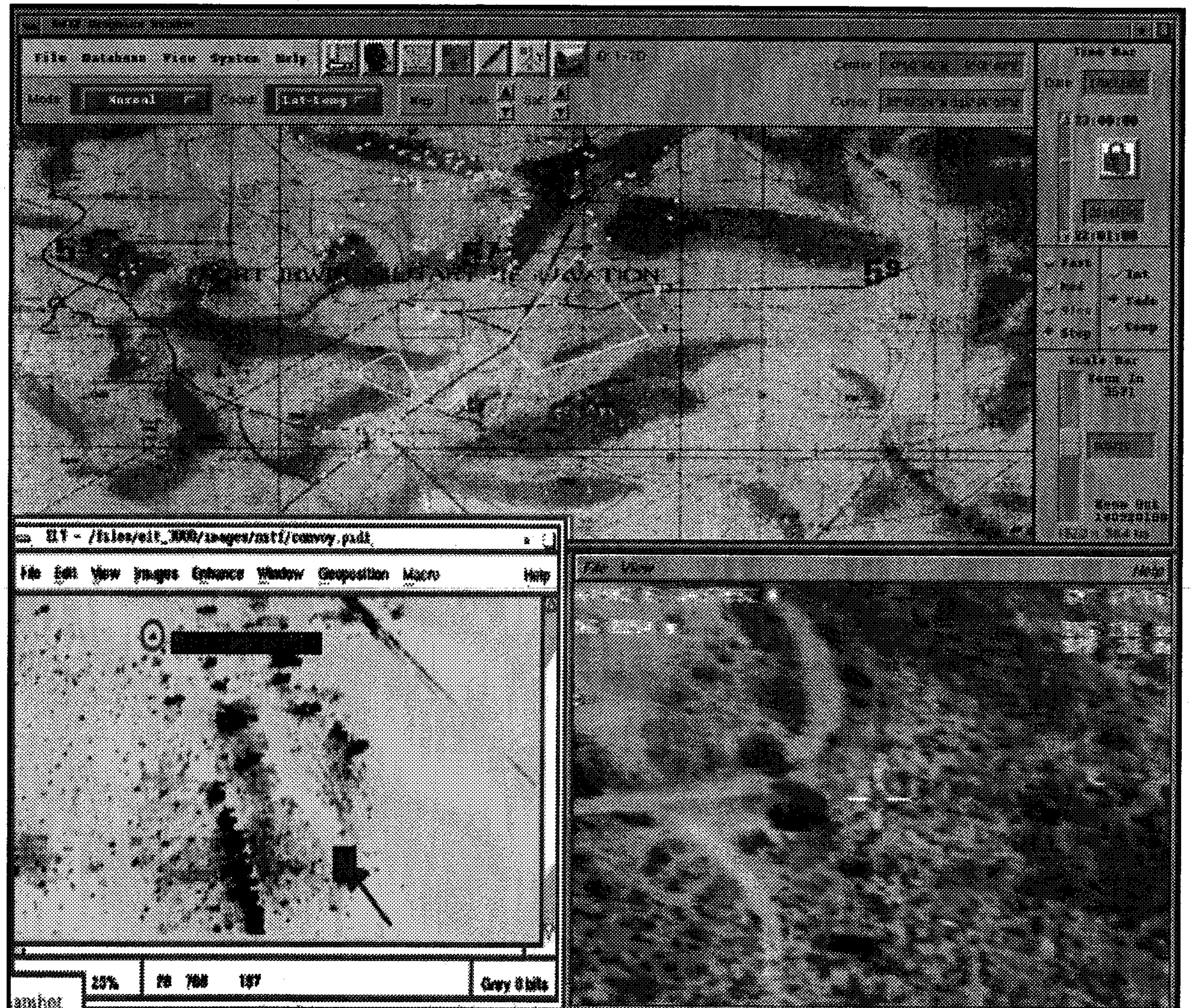


Backups

Commander Monitors the Battle



Common Ground Station Screen



STERLING SOFTWARE

Panel 1:
Requirements Generation for Total Battlespace Awareness

JAWS 99

Presented by

Tim Stolsig

Lead, Information Warfare Competency

Naval Aviation Systems Team

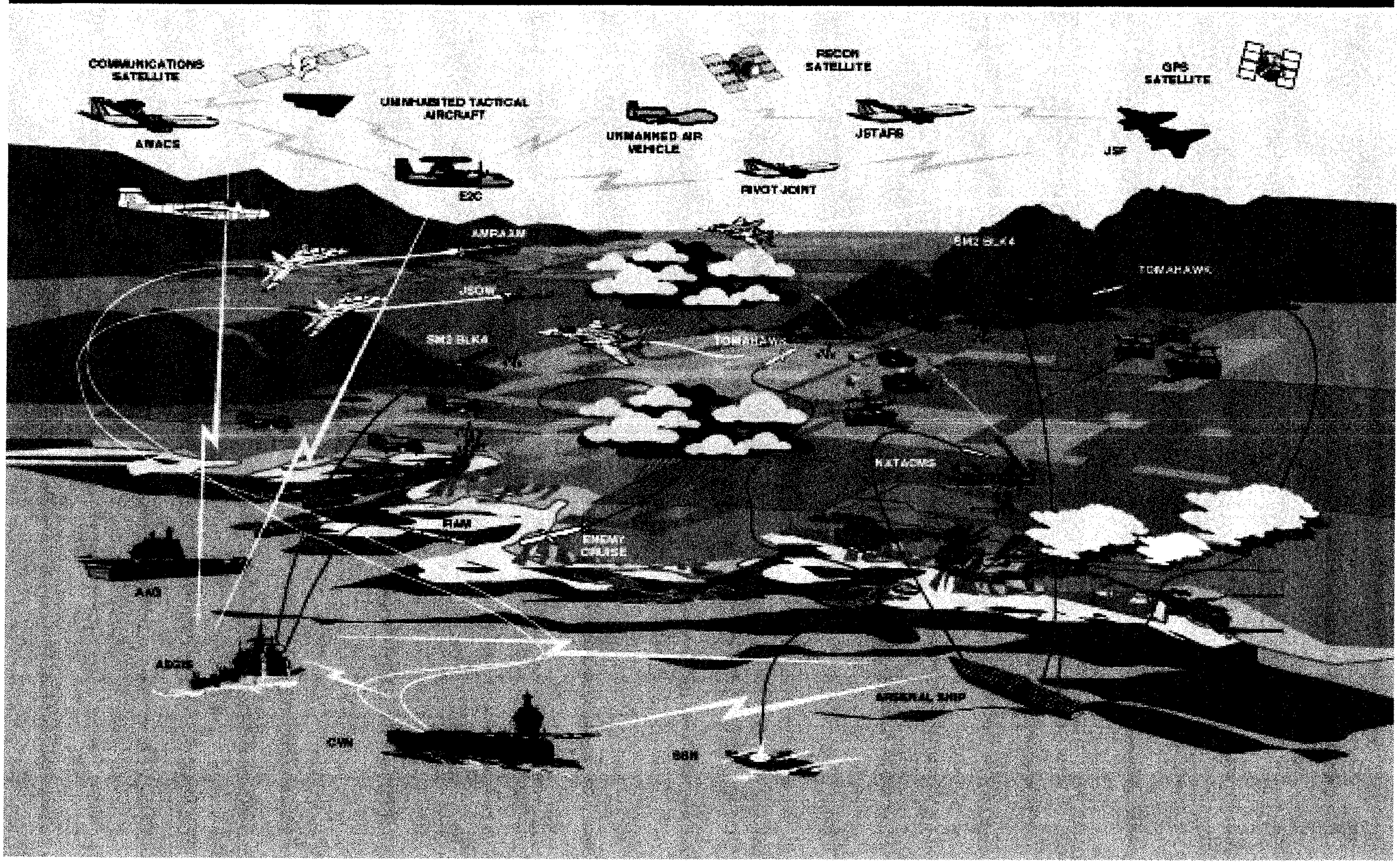
Requirements Generation

- Know the environment.
- Know your adversary.
- Know your strengths.
- Know your weaknesses.
- Your strengths and weaknesses, arrayed against your adversary's strengths and weaknesses, should reveal your requirements.

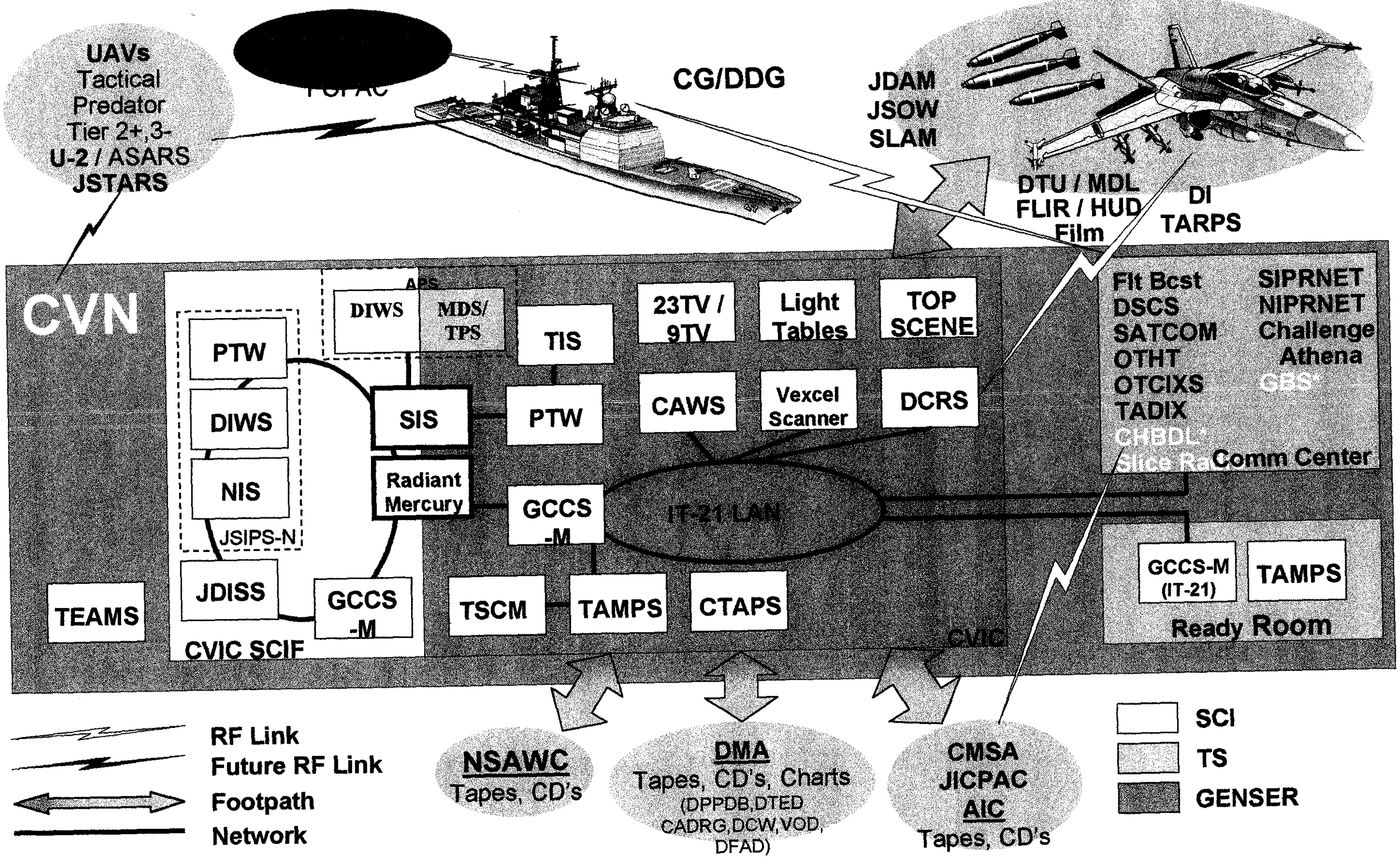
"Know the enemy and know yourself; in a hundred battles you will never peril. When you are ignorant of the enemy but know yourself, your chances of winning or losing are equal. If ignorant both of your enemy and of yourself, you are certain in every battle to be in peril."

Sun Tzu, The Art of War, Sixth Century B.C.

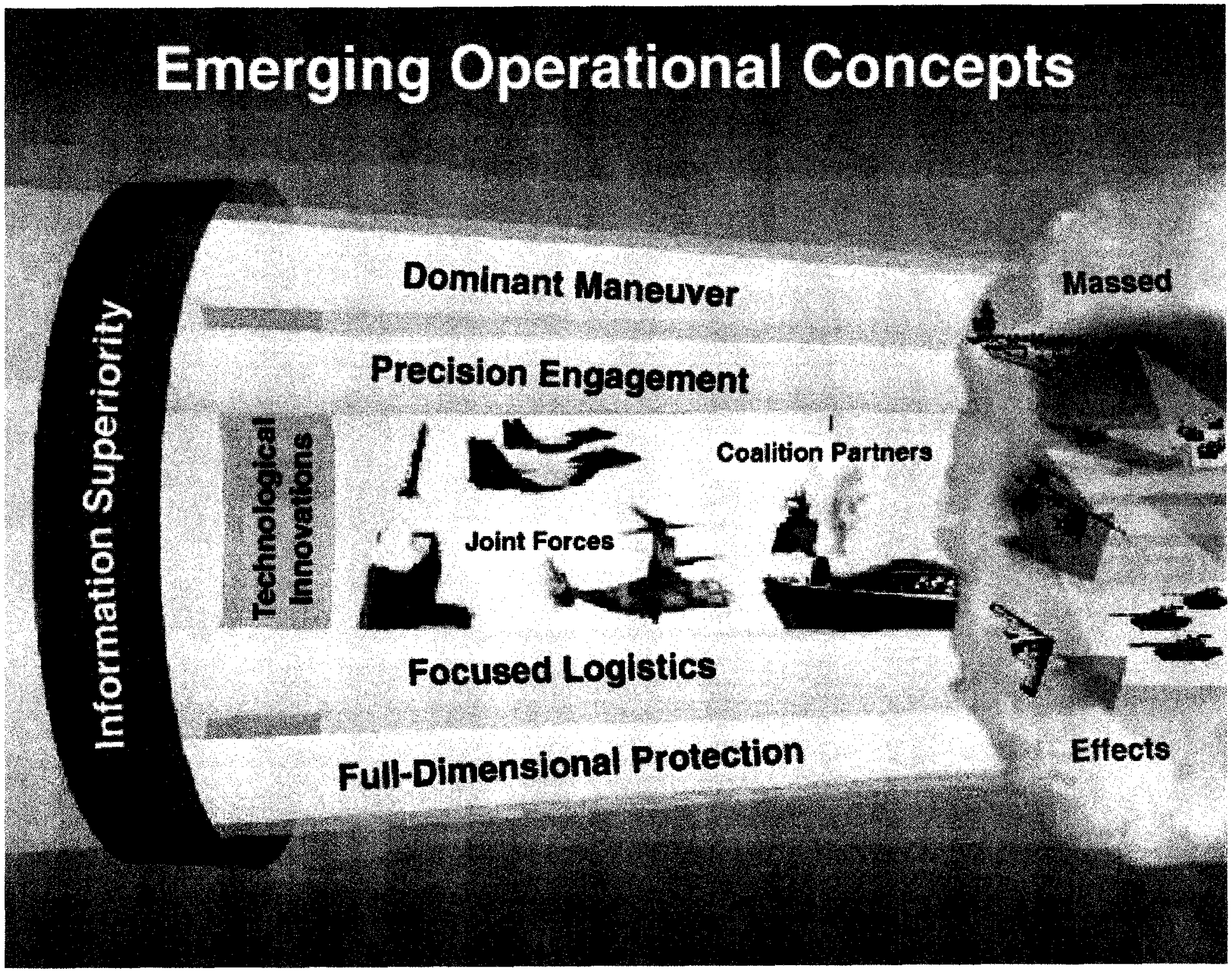
Today's Environment



Current CVIC



Emerging Operational Concepts



Operational Warfare Drivers

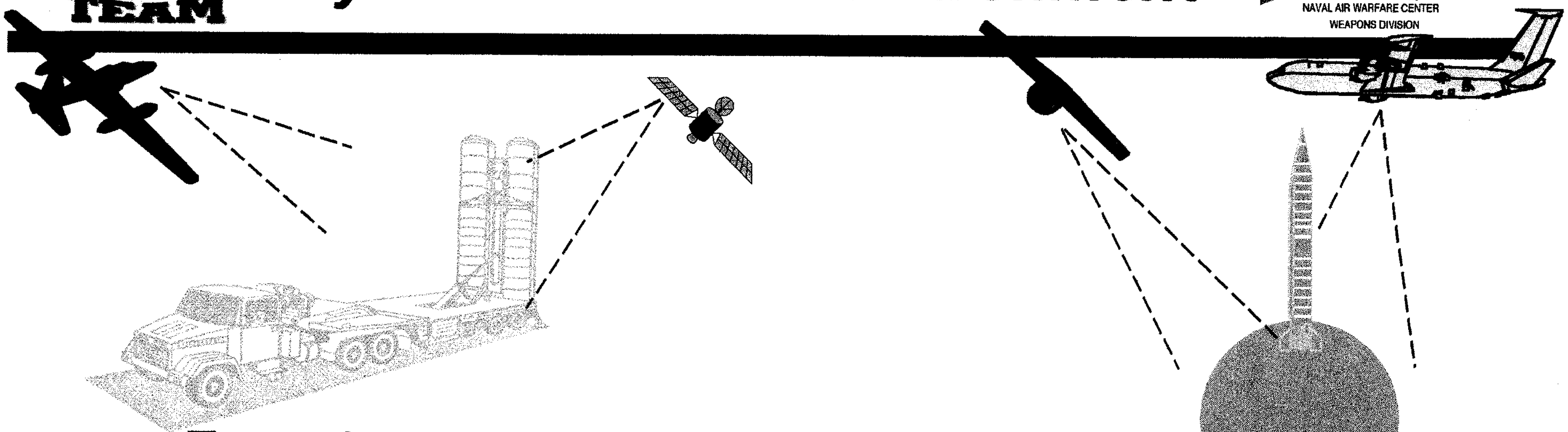
Aircraft	**Single seat, multi-mission, smart/ programmable**
Weapons	**Guided, standoff, autonomous**
Force Structure	**Fewer platforms, people, weapons**
Threat	**Lethal, mobile, electronically agile**
Operational Concepts	**Enable rapid, decisive, low loss victory**

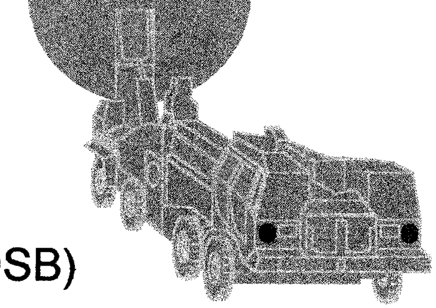
Improved planning methods and tools required to meet high information demands of modern strike warfare

NAVAL AVIATION SYSTEMS TEAM

Dynamic Mission Environment

INFORMATION WARFARE DIVISION
Tomorrow's Technology Today
NAVAL AIR WARFARE CENTER
WEAPONS DIVISION





- Emerging threat systems mobile/lethal
  - > 90%mobile, main threat to JSF (RADM Steidle)
- High interest "time critical" targets
  - Relatively few, but can drain JTF resources (1994 DSB)
- Battlefield changes dramatically <u>within traditional planning & execution timelines</u>

Mission planning is the pacing function in joint precision interdiction timeliness (1994 DSB)

Network Centric Warfare
Brave New World

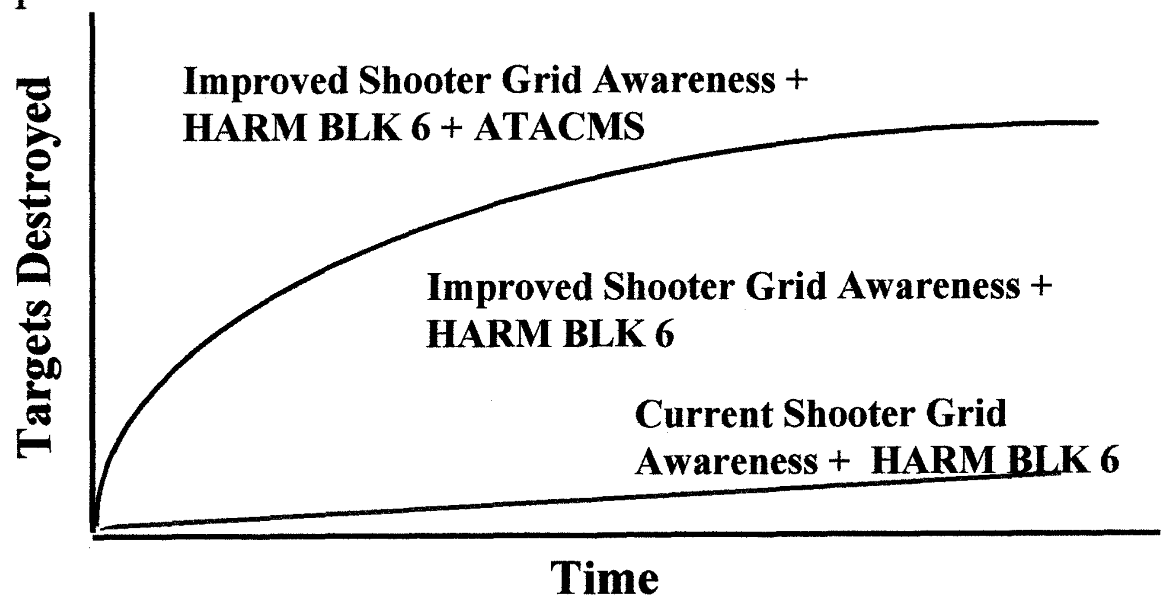
- Warfare which derives its power from the robust networking of a well informed but geographically dispersed force, enabled by:
  - Highly webbed information services
  - Timely access to all relevant and appropriate information sources
  - Value-added, automated command and control processes (to include high speed automated assignment of resources to need)
  - Integrated sensors hosted on the information network and closely coupled in time to the shooters and command and control processes
  - Weapons reach with precision and speed of response

Source: VADM Cebrowski, President, Naval War Collage, October 1998

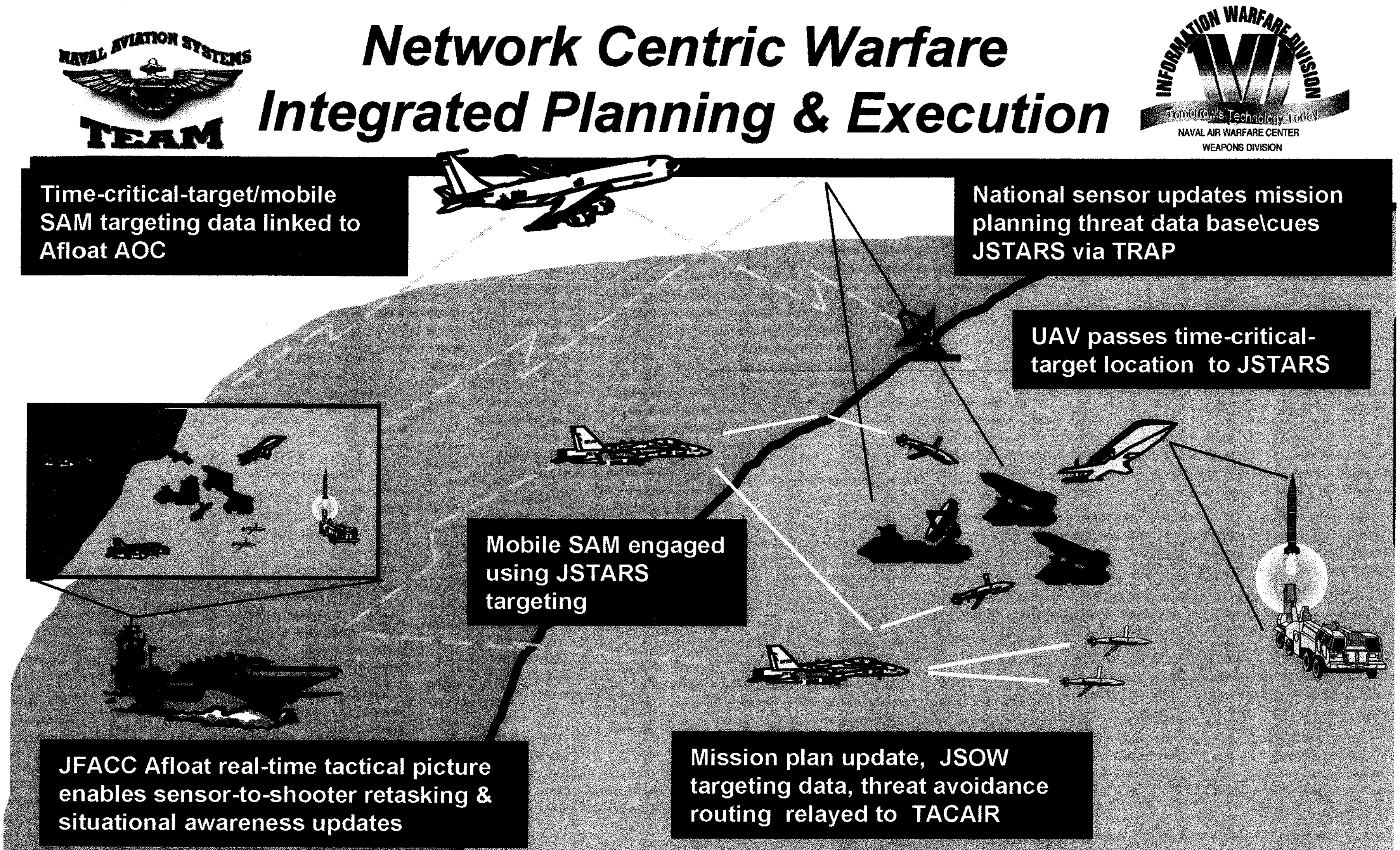
Network Centric Warfare Increases Joint Combat Power

Results for Precision Engagement

- **Operational Impact**
  - Dramatic Early Results
  - Greatest Rates of Change in Initial Phase of a Campaign
  - Inflicts Maximum Losses on the Enemy
  - Shortens Timelines
  - Locks out Enemy Options



Network Centric Warfare Integrated Planning & Execution



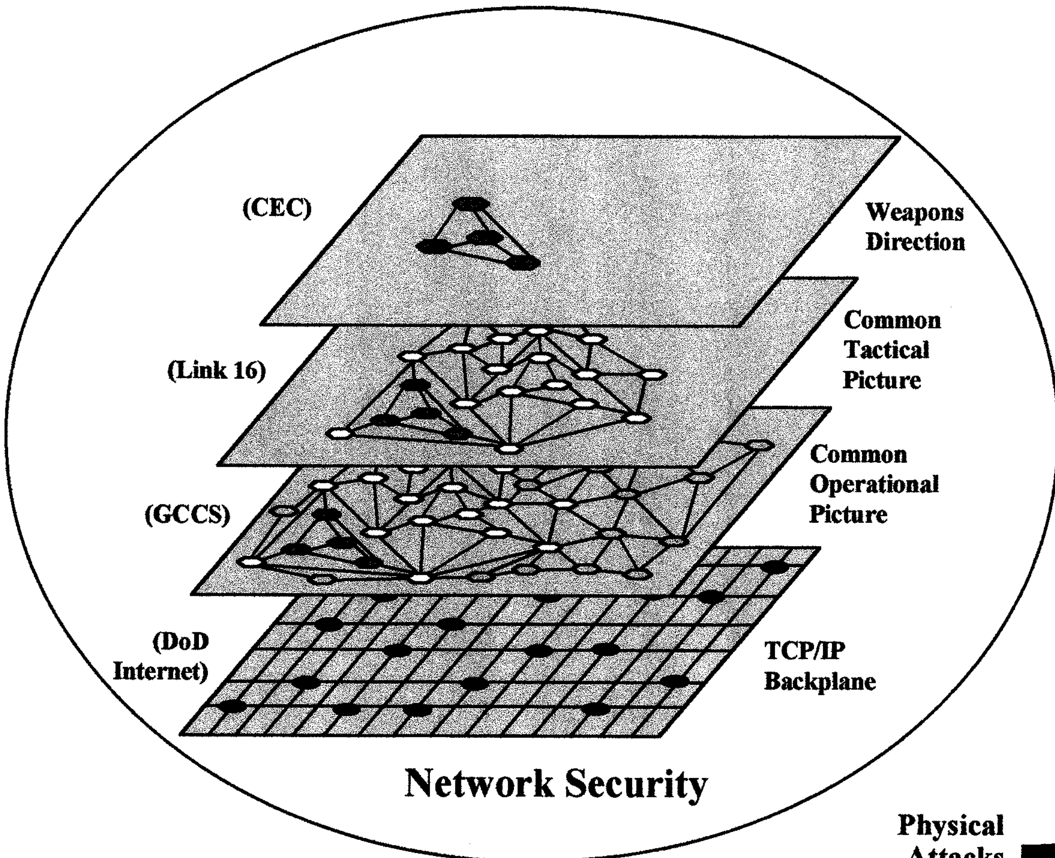
Time-critical-targets/advanced mobile threats demand integration of theater sensor data into real-time battle management and mission plan updates

NAVAL AVIATION SYSTEMS TEAM

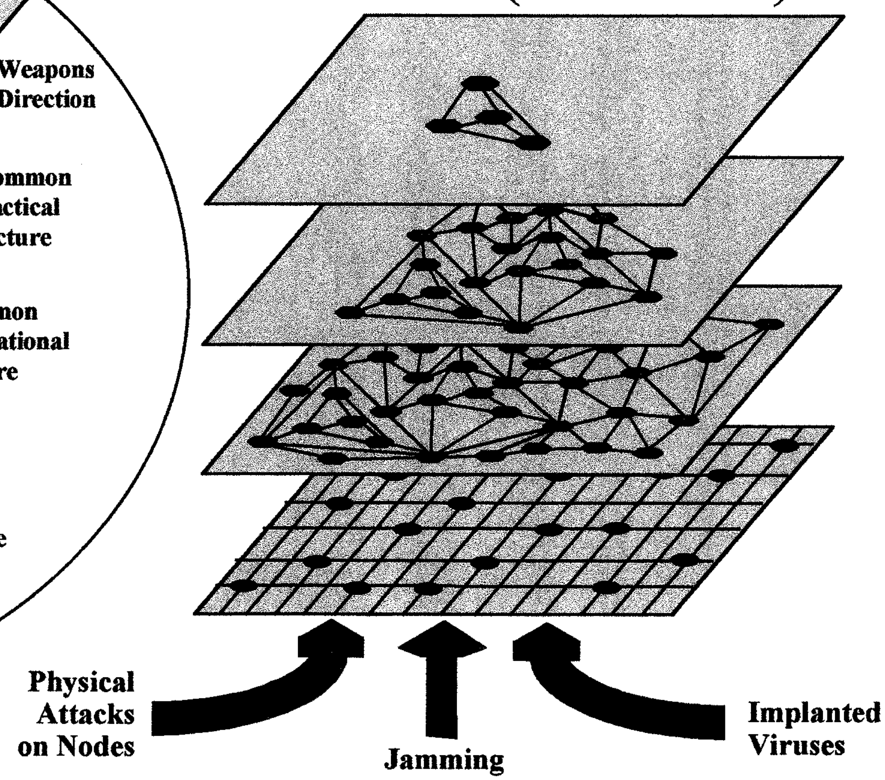
Information Warfare

INFORMATION WARFARE DIVISION
Tomorrow's Technology Today
NAVAL AIR WARFARE CENTER
WEAPONS DIVISION

Friendly Systems (IW Protect)

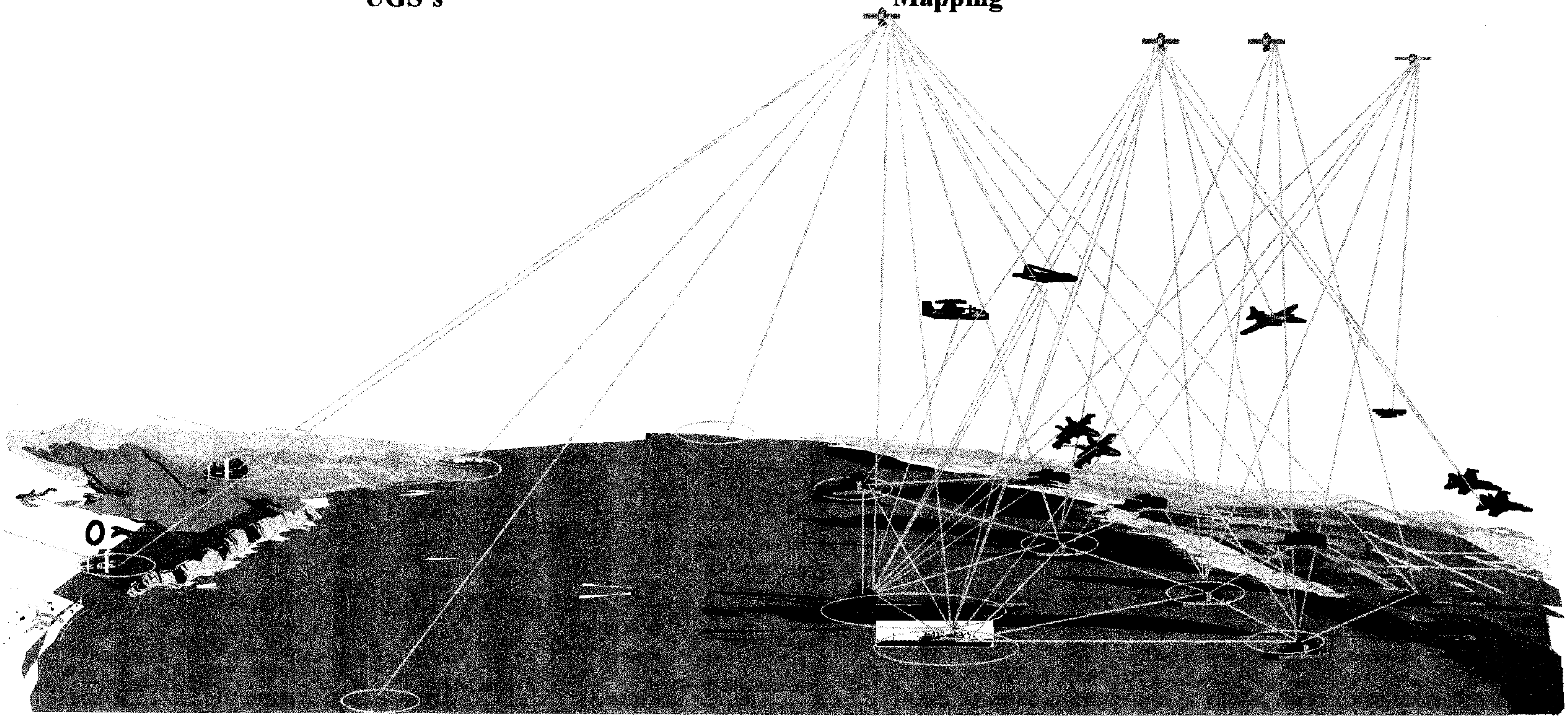


Enemy Systems (IW Attack)

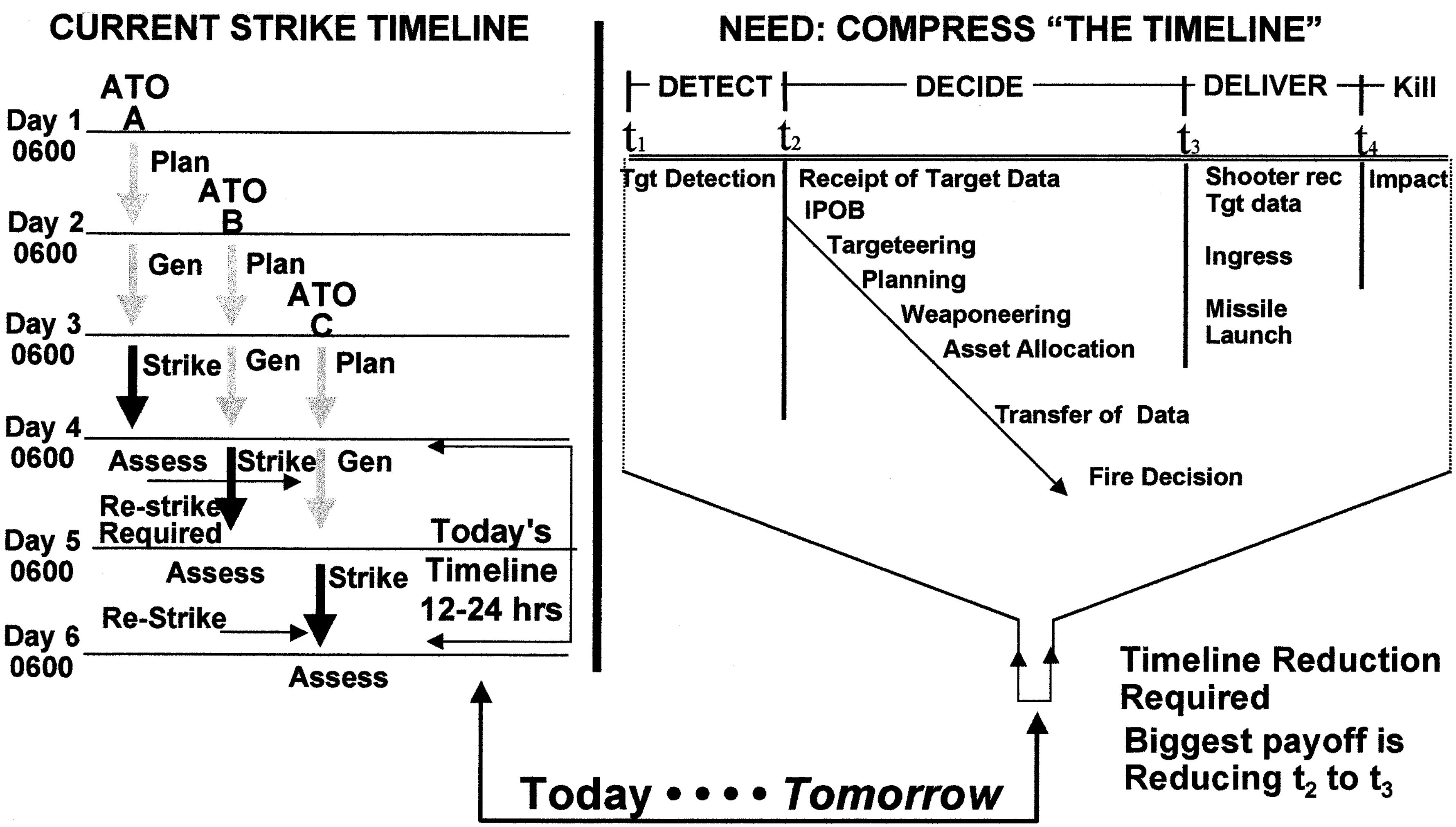


Scope of Land Attack Targeting 2010

Missions (day, night, wx)	Sensors	Launch Platforms	Weapons (to 600nm)	Targets
Strike	NTM	Manned A/C	Unguided	Soft, Hard, Buried, Camo'd
Air - Ground	Manned A/C	UCAV's	Guided	Fixed, Relocatable, Mobile,
Surface - Surface (NSFS)	UAV's	DDG's/SSN's	INS/GPS-only	Moving, TCT's
SEAD	Troops		Terminal Sensor	Point, Array
	UGS's		Mapping	

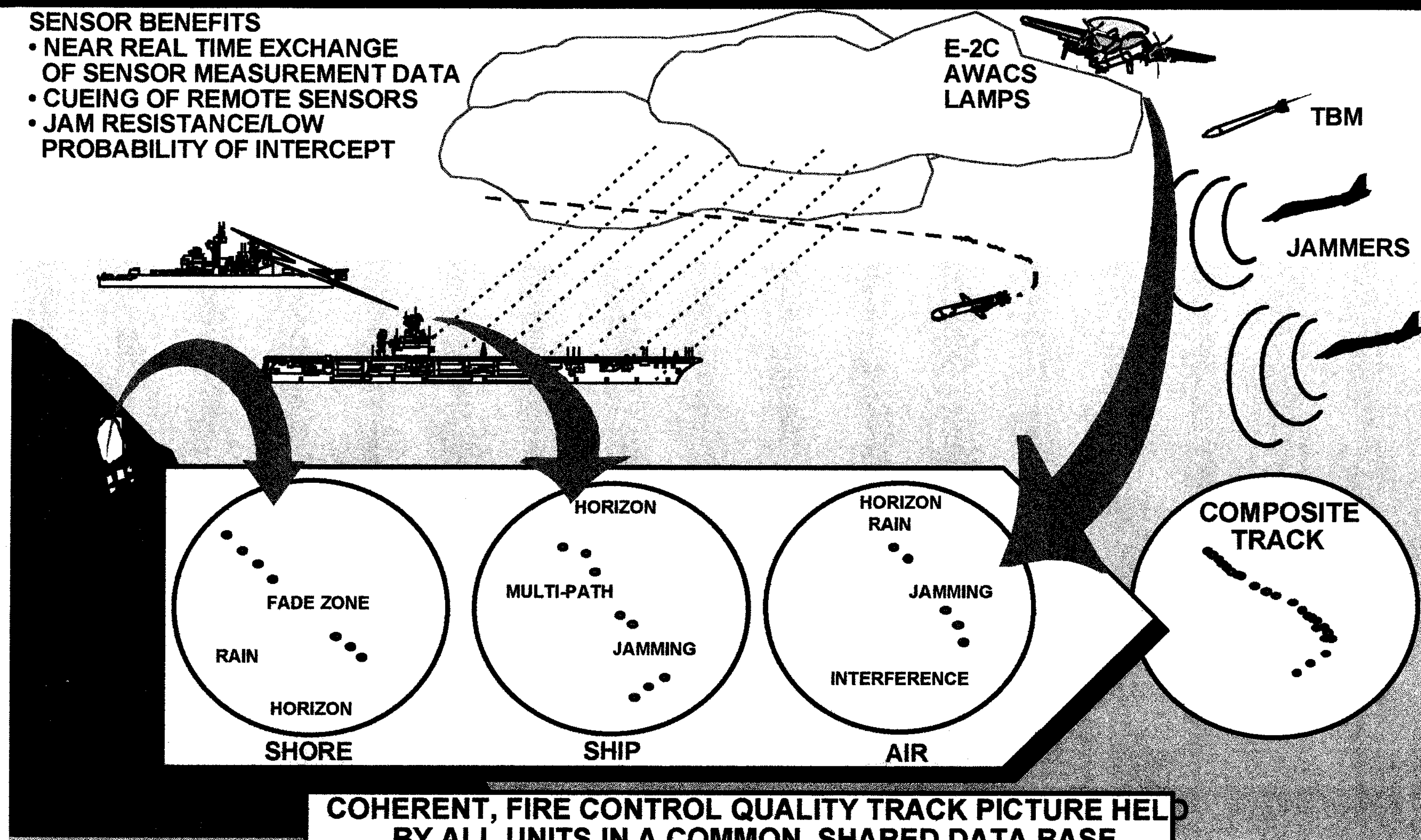


Strike Timeline



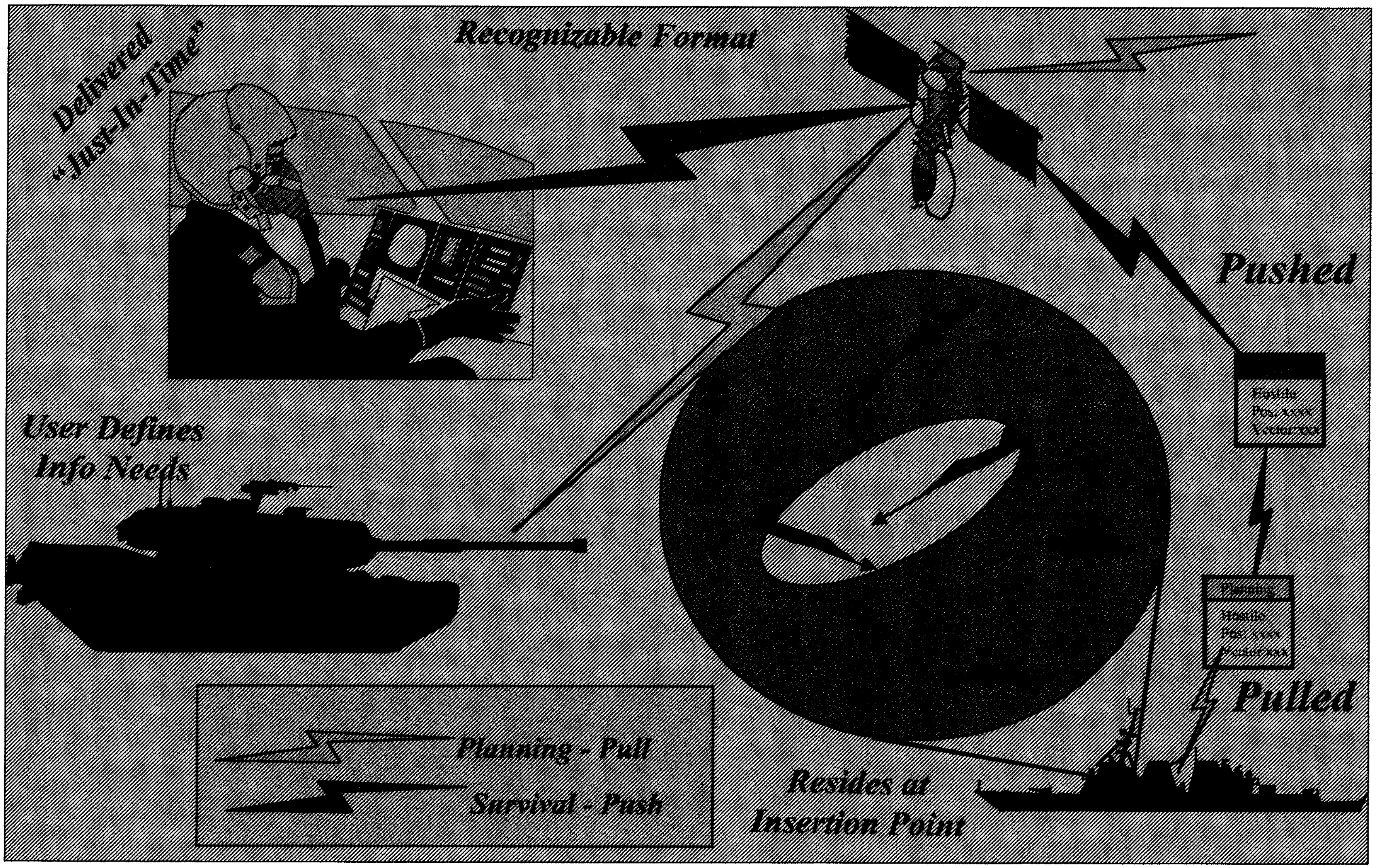
Cooperative Engagement Capability

SENSOR BENEFITS
- NEAR REAL TIME EXCHANGE OF SENSOR MEASUREMENT DATA
- CUEING OF REMOTE SENSORS
- JAM RESISTANCE/LOW PROBABILITY OF INTERCEPT



COHERENT, FIRE CONTROL QUALITY TRACK PICTURE HELD BY ALL UNITS IN A COMMON, SHARED DATA BASE

The Future: Seemless Integration



JAWS S3 Panel IV

Building the Analytical Bridge Between the Warfighter and the Engineer

Mr. Allen [illegible]

Directorate of Comma[illegible]

[illegible]

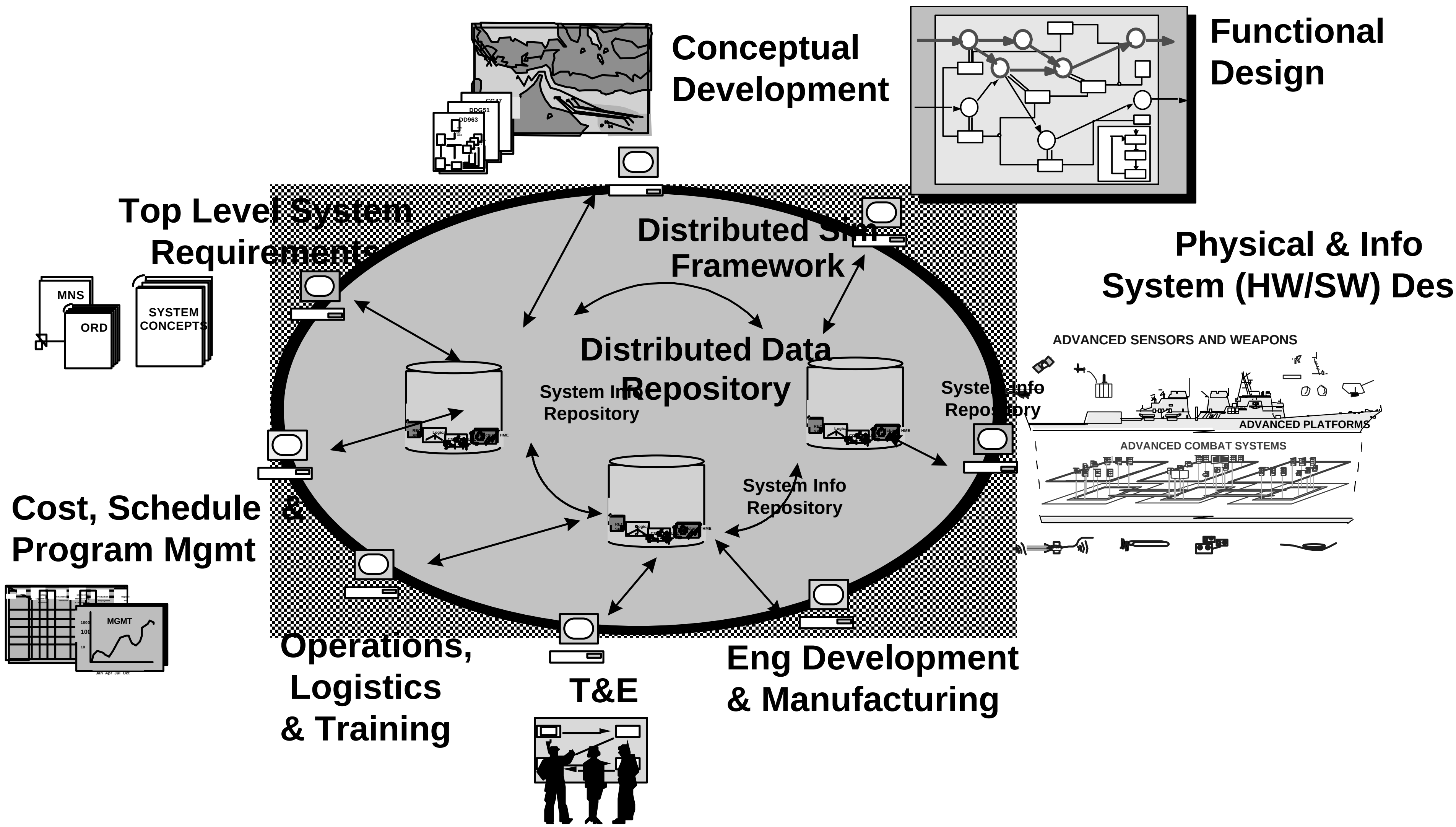
16 June 1999

Panel IV

- Task: Build an analytical bridge between the warfighter and the engineer
-
  - **Byproduct: Create synergy (vice tension) between "requirements pull" and "tech push"**
-
- Framework: Simulation Based Acquisition
  - **Examples of 'bridges':**
    - **JSF**
    - **USAF C2**
  - **Some bridge building tools:**
    - **AFRL Virtual Testbed**
    - **JMASS**

SBA Operational Concept Illustration

(Digital Information Based Process)



Extensive Re-use Across Phases and Across Acquisition Programs

Simulation Based Acquisition

- Revamp acquisition process to capitalize on the advances, advantages & potential of digital information technology
-
- Use shared access to distributed information to:
  - Closely link stakeholders in product development
  - Facilitate iterative, spiral development
  - Facilitate collaborative, concurrent processes, IPPD
  - Create synergy between requirements pull & technology push

Anticipated SBA Impact on Analytical Link

- Better, more consistent models
- More support for development of M&S tools
- Better access to data, authoritative information
- Better synthetic environments
- Earlier access to product information
- Better understanding & definition of requirements
- Better linkage of requirements to performance
- Better understanding of thresholds
- Easier to identify & focus on prime OT&E areas
-

SBA Analytical Linkage: Examples

DIRECTORATE OF COMMAND & CONTROL

-
-
- Joint Strike Fighter
-
- USAF Command & Control

SBA Analytical Linkage Example: JOINT STRIKE FIGHTER

- **Delay locking in requirements**
  - **JSF has used ‘interim requirements’; no ORD until ‘00**
- **Evolve requirements with an integrated set of simulations**
  - **Campaign/mission modeling with constructive simulations (95-96)**
  - **Virtual simulations (w/man-in-the-loop)**
  - **Interactive digital simulations to evaluate specific functional requirements (97-99)**
  - **Virtual Strike Warfare Environment exercises (98)**
- **Provide early weapon system experience for warfighters for conceptual development**
- **Use SBA analytical construct for cost & operational performance trades, within warfighter CONOPS**

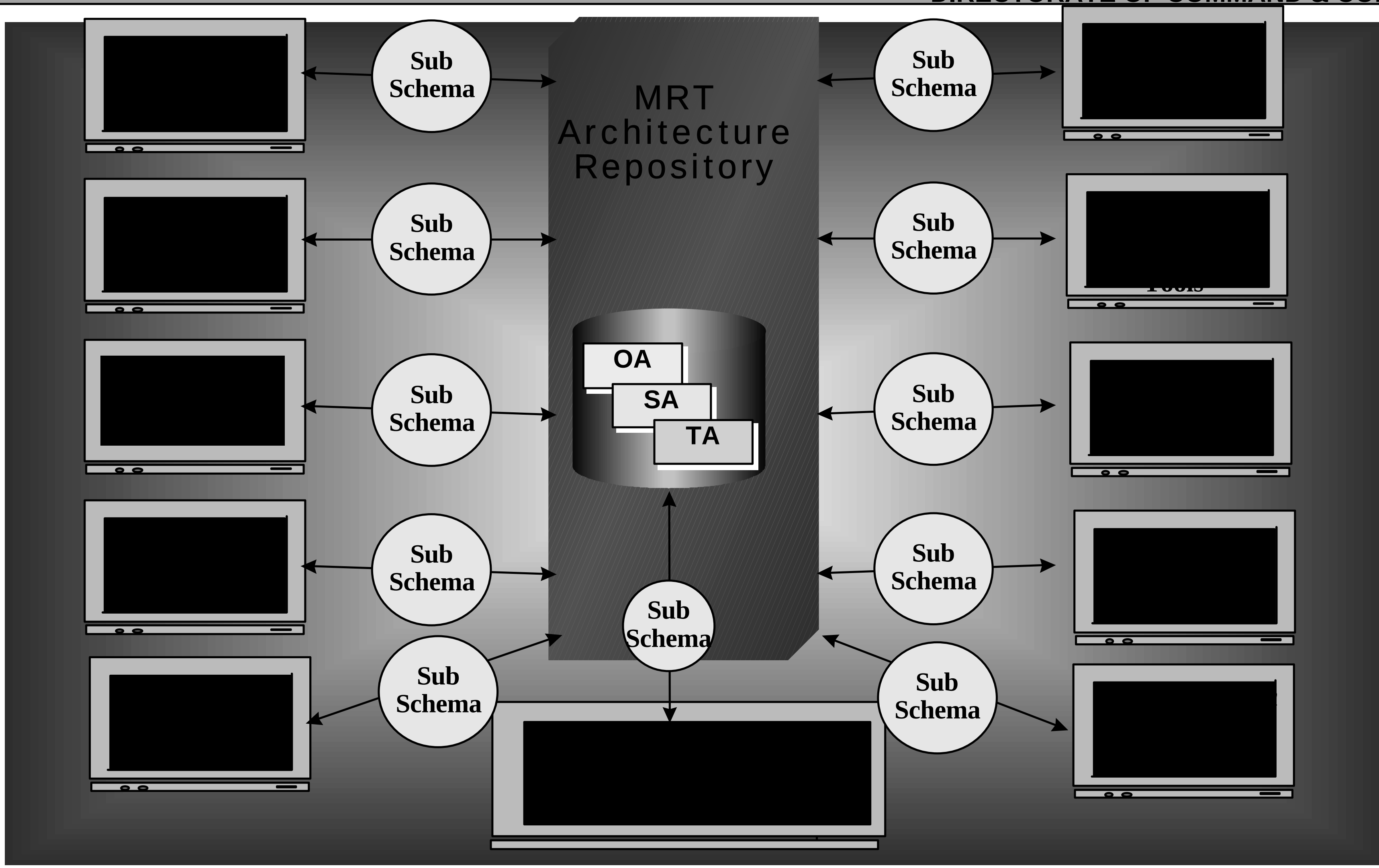
SBA Analytical Linkage Example: AF Command & Control

- **ESC SBA initiative:**

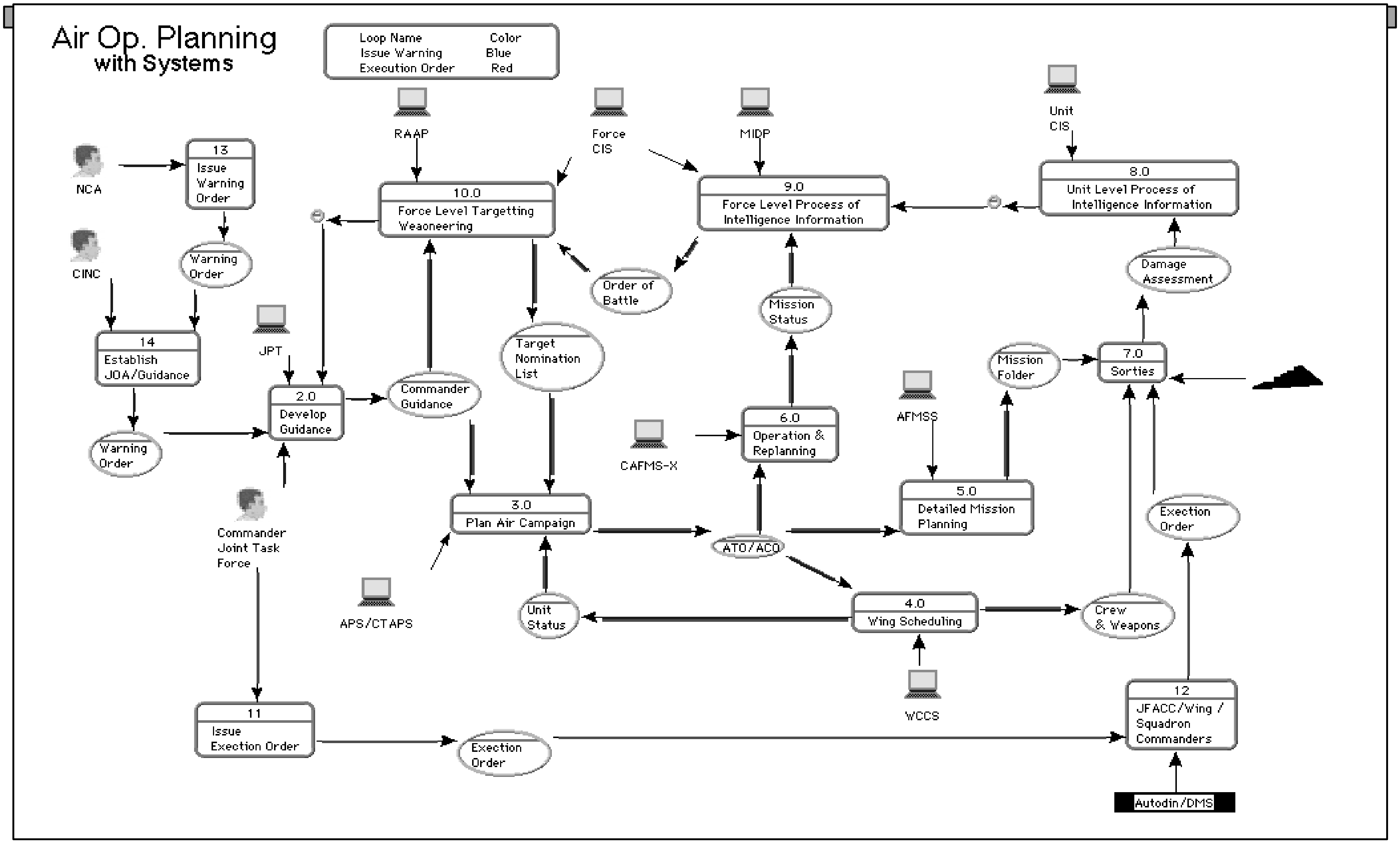
  Link requirements M&S tools/data (used by C4ISR operators) with system design & build tools/data (used by C4ISR developers)

- **Intent:**
  - Provide single continuous, traceable flow of data from operational need to system capability
  - Integrate/map CINC C2 requirements with Service baseline system capability
  - Merges Joint C4ISR Architecture & Planning System (JCAPS) and proven model-based system engineering process (Model Reference Technology)

SBA for C2 at ESC: Model Reference Technology



Integrated Operational/Systems Architecture Threads



SBA Analytical Tools: Examples

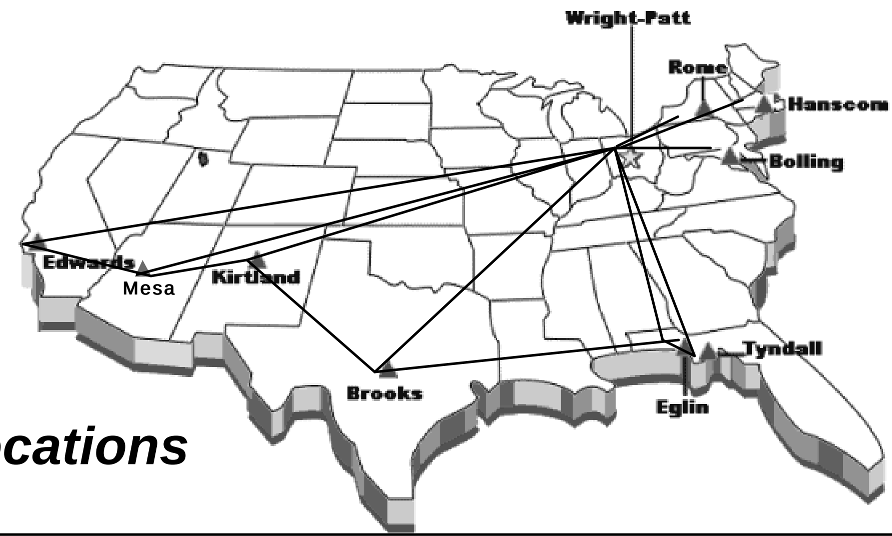
-
- AFRL Collaborative Enterprise Environment
-
- JMASS

AFRL Collaborative Environment

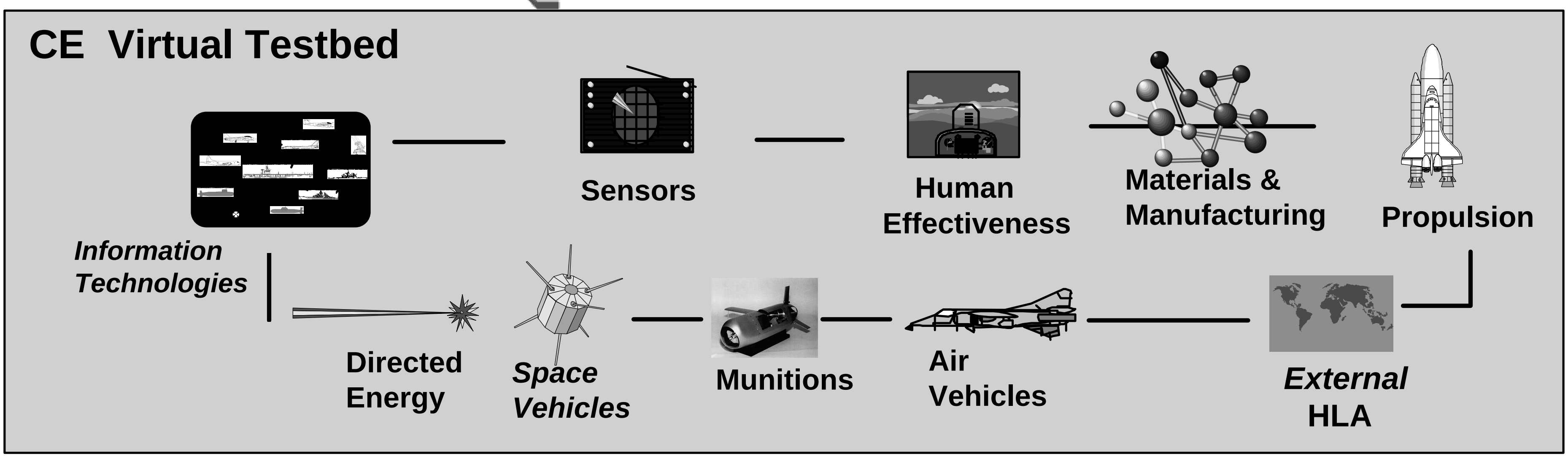
Virtual Testbed

DIRECTORATE OF COMMAND & CONTROL

- Requirements Definition
- Technology Integration
- Survivability/Vulnerability
- Military Worth
- Virtual Flight Tests
- Seamless Constructive/ Virtual Simulation



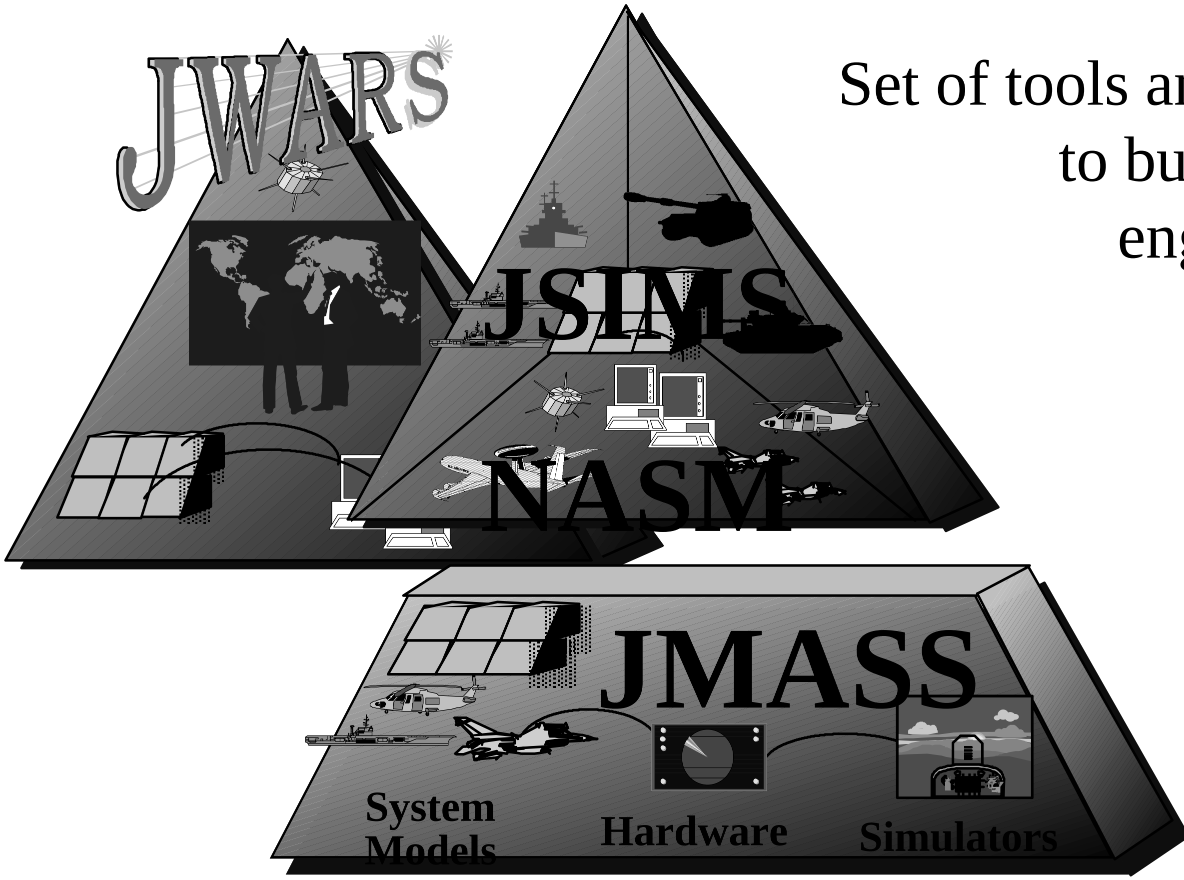
AFRL Locations



"The Network is the Simulator"

SBA Analysis Tool: JMASS

DIRECTORATE OF COMMAND & CONTROL

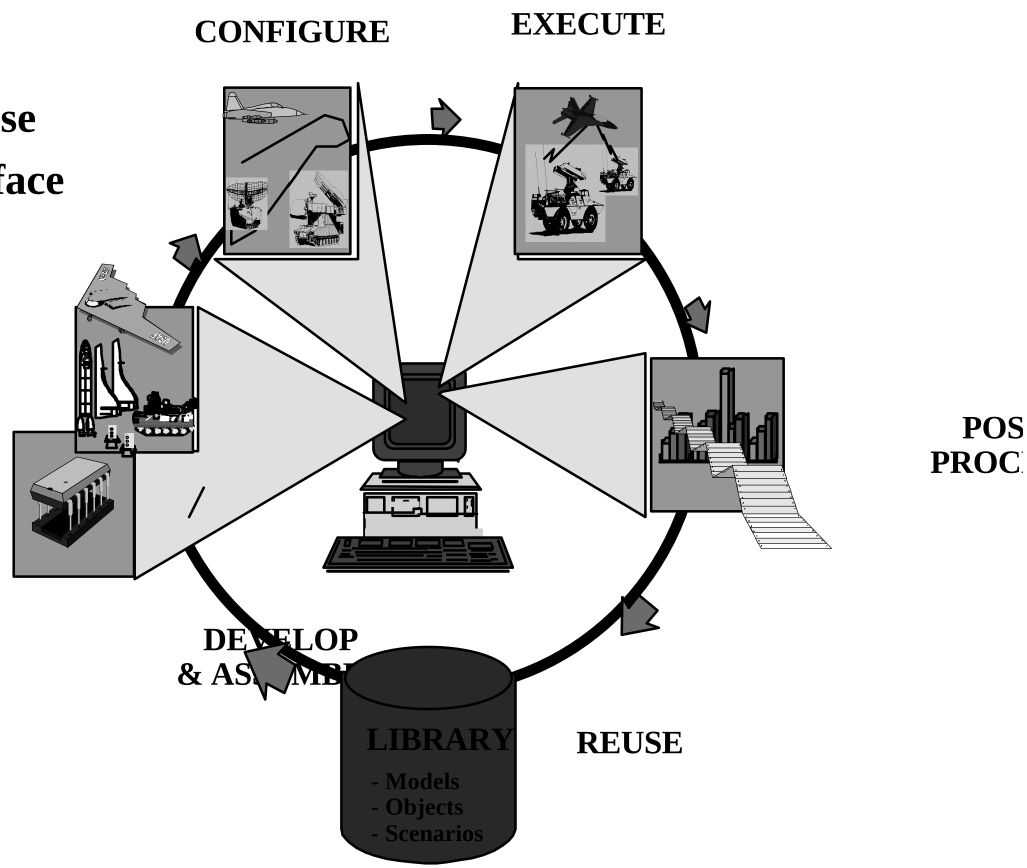


Set of tools and services that allow user to build, configure and execute engineering and engagement level simulations

Now a Joint Program

The Essence of JMASS

- **Model Standards**
  - **SEI Software Structural Model for Reuse**
  - **Model Application Programming Interface**
- **Simulation Support Environment**
  - **Simulation Engine**
  - **Communications Architecture**
  - **Visual Development Tools**
  - **Analysis Tools**
  - **COTS & Legacy Tool Interface**
- **Model Library & Repository**
  - **Local Model and Data Library**
  - **Remote Model Repository**
  - **Contains DIA-validated threat models**



Yield is common, reusable, interoperable, validated models

Summary

- Simulation Based Acquisition provides framework to analytically link warfighter to developer, other stakeholders
- SBA approach will emphasize and improve analytical tools, product models, visualization
- SBA will enhance access to critical authoritative information needed for warfighter and developer tradeoff decisions
- Programs are already embracing the SBA construct

High Range Resolution Profile Generation Using Sensor And Signature Simulation

Bassem R. Mahafza*, Anthony C. DiRienzo*, J. Todd Worthington*, W. Keith Hardy*, W. Talmadge Robinson*, Susan D. Campbell**, and Virginia P. Kobler**

* Colsa Corporation, Huntsville, AL

** US Army National Missile Defense Ground Based Radar Project Office

Abstract

Sensor and Signature Simulation (SASS), is a simulation which was developed for the National Missile Defense (NMD) Ground Based Radar-Project Office (GBR-PO) to produce Radar Cross Section (RCS) and target signatures. It is utilized within the NMD-GBR Hardware in the Loop (HWIL) Test-bed, as well as the THAAD Radar Test-bed. Target High Range Resolution (HRR) profiles generated by SASS are used to emulate and execute tactical radar operations. Target models are built up from simple component types, such as flat plates, frustums, spheres/spheroids and fins whose known radar signature is characterized in terms of scattering centers. The radar signatures of the complete target model are determined by reducing the target to a list of effective scatterers. In this paper, we will show how to build and execute targets using SASS, and how to generate the corresponding HRR Principle Polarization (PP) and Orthogonal Polarization (OP) range profiles. Comparisons with real world, and other models (such as Xpatch), will be used as a means of validation. The most important attribute of SASS is speed of execution. Additionally, it is quite easy to build and execute targets using SASS. Wide Band (WB), NB, and HRR -PP and -OP profile examples will be used.

I. NMD GBR HWIL Test-bed Block Diagram [1]

Figure 1 shows a block diagram for the NMD-GBR HWIL Test-bed.

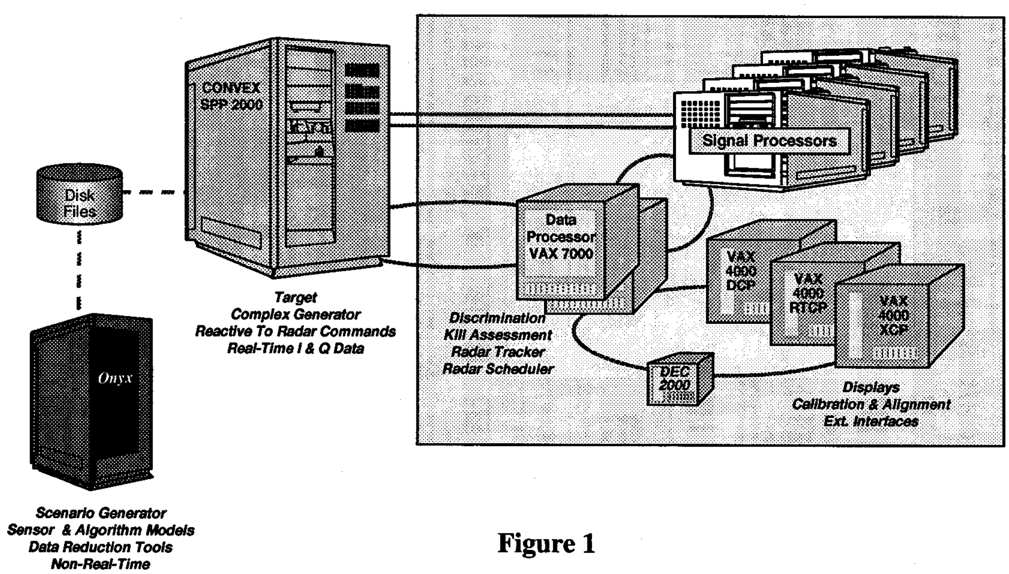


Figure 1

The Target Complex generator (TCG) was developed to digitally simulate the antenna, Beam Steering Generator (BSG), transmitter, waveforms, receiver and Analog to Digital (A/D), of the tactical radar in all three monopulse channels. The TCG provides the required signals to the Data Processing Equipment (DPE), via a Fiber optic Digital Data Interface (FDDI), and to the Signal Processing Equipment (SPE), via a High Performance Parallel Interface (HiPPI).

II. SENSOR AND SIGNATURE SIMULATION (SASS) [2-5]

SASS contains models of the GBR radar signal and data processors to provide for an all digital simulation of the radars. SASS provides high fidelity representation of modern high frequency, coherent chirp radar. All digital models within SASS are systematically constructed and executed, through a user friendly set of graphical user interfaces (GUIs). The GUIs also allow for extensive generation and graphical display of targets, engagement and signatures. This includes, three-dimensional (3-D) static and dynamic target representation, target scattering static patterns, radar engagement (range, altitude, aspect angle, etc.) histories, RCS and phase histories, stacked narrow band, medium band and wide band compressed pulse shapes and measurements. Sensor error analysis are also available. Figure 2 contains SASS external interface block diagram and shows the host and interfaces for the SASS application.

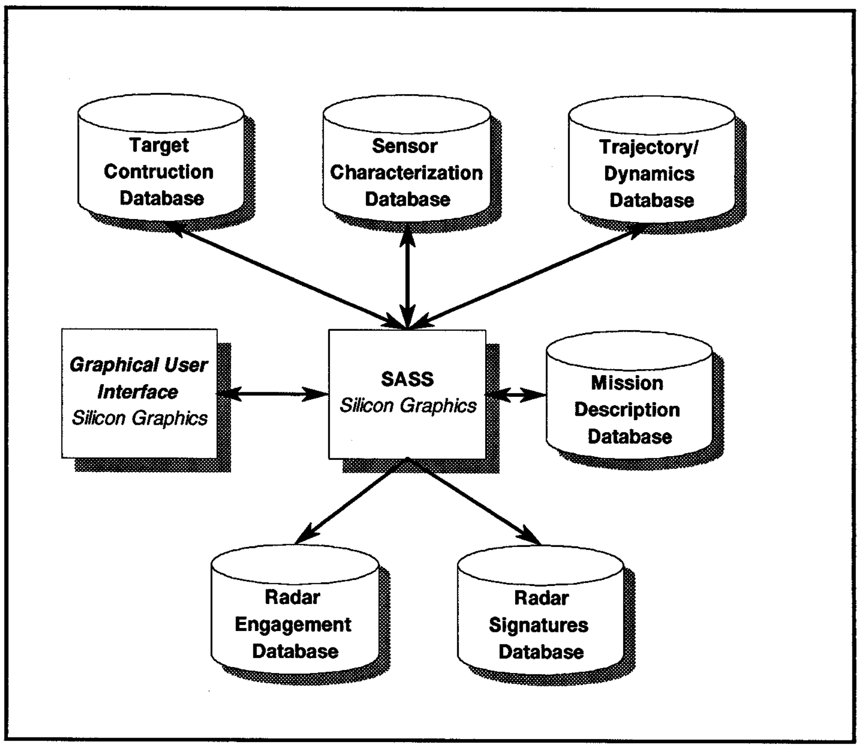


Figure 2

Target models are built up from simple component types, such as flat plates, frustums, spheres/spheroids and fins whose known radar signature is characterized in terms of scattering centers. The radar signature of the complete target model can then be determined by reducing the target to a list of effective scatterers, complex amplitudes and their positions as projected along the radar line of sight. The most important attribute of SASS is speed of execution. For example, using a Silicon Graphics O2 machine SASS produces an output in less than three seconds, even for the most complex targets. Additionally, it is quite easy to build and execute targets within SASS

Scattering center characterization describes the processing necessary to determine where the effective scattering centers of the target are located and in what manner they contribute to the radar signature. This capability involves the determination of visible scattering centers and the corresponding complex electromagnetic scattering amplitude. This characterization calculates the complex electromagnetic scattering amplitude using an extension of the scattering center approximation developed by Crispin and Maffet. In this approximation the targets are first broken up into geometrical sub-elements, then Physical Optics (PO) is used to calculate the contribution from surface returns of the sub-elements and the Geometrical Theory of Diffraction (GTD) is used to calculate the diffraction contribution from the joints and edges of these sub-elements. The PO returns are calculated for surfaces perpendicular to the line-of-sight, where PO is a good approximation, and GTD is not. For the other cases, GTD is used. Since our radar has a monostatic arrangement, the GTD returns come only from points on the edges where the edge is perpendicular to the line of sight. Thus, both the PO and GTD returns are equivalent to returns due to effective scattering centers, located at the surface edges for PO contributions and located at the edges/joints nearest to the radar for GTD contributions. With SASS, the calculations are taken one step further, the remaining unshadowed scattering centers are then summed coherently (taking into account the distances from the radar of each scattering center along the radar line-of-sight), giving a total complex scattered return towards the radar. From this, the target RCS is calculated.

Figure 3.a shows a typical generic target (Re-entry Vehicle (RV)) constructed using SASS, while Figure 3.b shows the corresponding Narrow Band (NB) RCS (dBsms) at X-Band versus aspect angles (degrees). Figure 3.c Shows the corresponding Wide Band (WB) target signature at the same frequency.

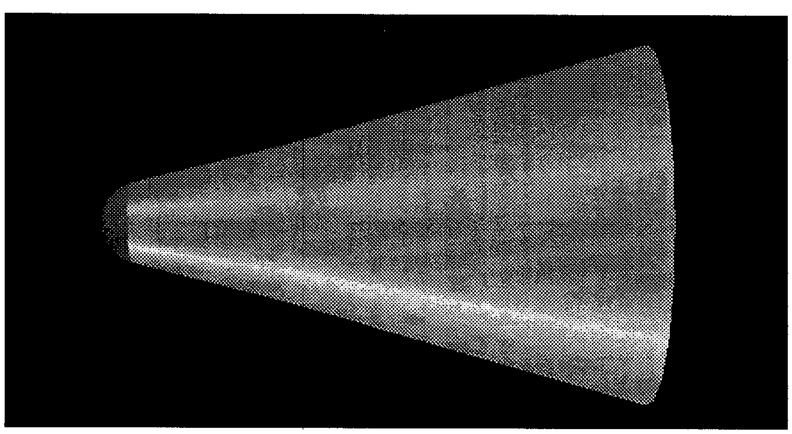


Figure 3.a

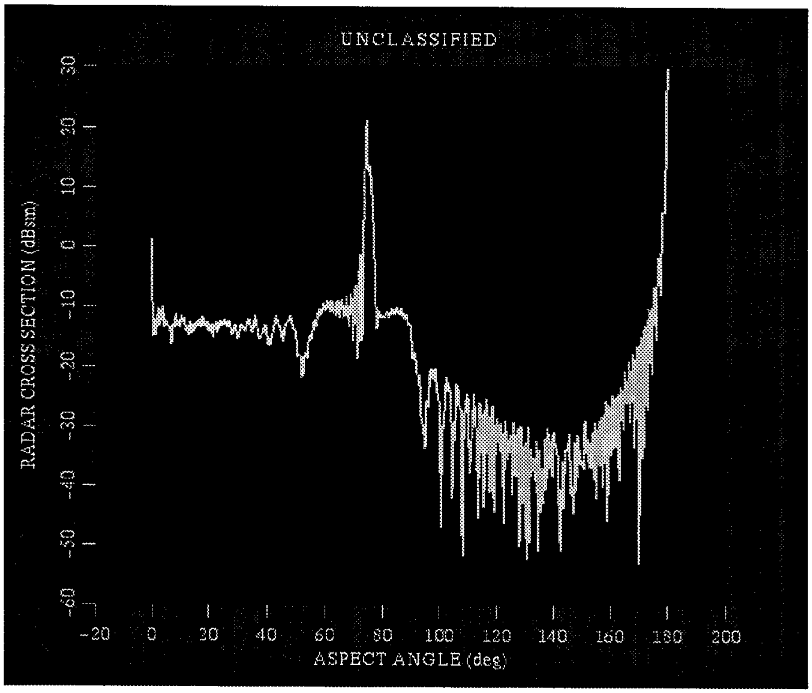


Figure 3.b

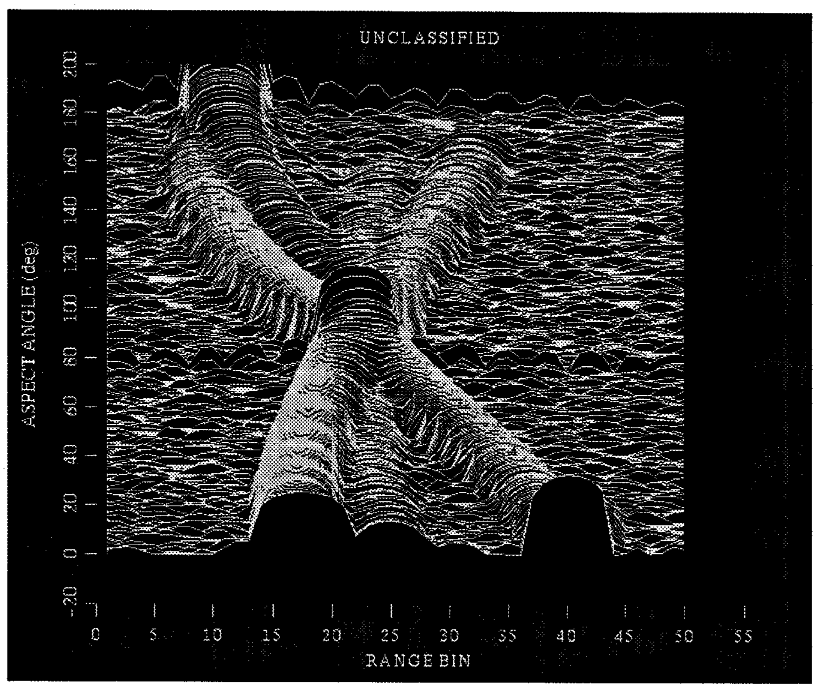


Figure 3.c

III. Stepped Frequency Waveforms and High Range Resolution Profiles [6-8]

Discrete Fourier Transform (DFT) processing of a series of I and Q samples collected on a pulse by pulse basis can be used to generate a high resolution range profile of an isolated target. This can be accomplished by transmitting a sequence or burst of Narrow Band (NB) monotone pulses that are stepped in frequency. Such pulses are referred to as Stepped Frequency waveforms (SFWF). These pulses illuminate a target located in the far field, and after the radar receiver collects a burst of echo pulses, the radar processor Fourier transforms the signal into a target range profile. The processed target range resolution is $c/(2N\Delta f)$ where c is the speed of light, N is the number of steps in the burst, and Δf is the frequency step size.

In general, the Pulse Repetition Frequency (PRF) for a SFWF, during the nth step, can be expressed as

$$f_n = f_0 + n\Delta f \qquad \text{(EQ 1)}$$

where f_0 is the radar operating frequency and Δf is the frequency step. Assuming returns form a stationary target at range R, then the nth video quadrature components for a processed SFWF are

$$x_I^n(t) = C_n \cos\psi_n \qquad \text{(EQ 2)}$$

$$x_Q^n(t) = C_n \sin\psi_n \qquad \text{(EQ 3)}$$

where $\psi_n = (-4\pi R f_n)/c$, C_n is the amplitude for the nth return. The complex video signal is then given by

$$x_n(t) = x_I^n(t) + jx_Q^n(t) = C_n e^{\left[j\left(\frac{4\pi R f_n}{c}\right)\right]} = C_n e^{j\psi_n} \qquad \text{(EQ 4)}$$

It follows that the sampled quadrature components are made of discrete samples the target reflectivity in the frequency domain. And hence, this information can be transformed into range refelcivity series by using the Inverse DFT (IDFT). More precisely, the synthesized range profiles is given by,

$$H_l = \sum_{n=0}^{N-1} \frac{1}{N} C_n \, e^{\left[j\left(\frac{4\pi R f_n}{c}\right)\right]} \, e^{\frac{j2\pi nl}{N}} \qquad ;(0 \le l \le N-1) \qquad \text{(EQ 5)}$$

The instantaneous frequency of the nth video signal can be evaluated as

$$f_d = \frac{2R}{c}\dot{f}_n + \frac{2f_n}{c}\dot{R} \qquad \text{(EQ 6)}$$

where the first term of the right hand side of (EQ 6) corresponds to the frequency change associated with changing the transmitted frequency and range to the target. Alternatively, the second term is associated with the targets induced Doppler due to its motion.

The unambiguous range associated with a SFWF can be found to be

$$R_u = \frac{c}{2\Delta f} \tag{EQ 7}$$

and the corresponding range resolution is

$$\Delta R = \frac{c}{2N\Delta f} \tag{EQ 8}$$

As indicated by (EQ 8) the total number of frequency steps and the step size determine the final synthesized range resolution. Thus, one can perhaps conclude that by increasing the step size then range resolution can be improved. This is true, however, in order to avoid aliasing one must choose the frequency step so that

$$\Delta f \leq \frac{c}{2E} \tag{EQ 9}$$

where E is the target extent in meters. Additionally,

$$\Delta f \leq \frac{1}{2\tau} \tag{EQ 10}$$

where τ is the pulse width.

IV. Utilization of SFWF within SASS

We developed a SFWF processing module within SASS in order to generate HRR profiles of SASS targets. For this purpose, each sub-pulse within a burst is Linear Frequency Modulated (LFM), where the bandwidth corresponds to Δf. The choice of the number of steps within a burst and the step size, are dynamically computed on the basis of the target extent and the desired bandwidth. Further more, HRR profiles for SASS targets are produced for both Principal Polarization (PP) and Orthogonal Polarization (OP). Both PP and OP signatures along with their ratio, are then stored in binary format, for later use in the GBR HWIL test-bed.

The NMD-GBR-PO requested that all of the HWIL entities, including SASS, undergo a Verification, Validation, and Accreditation (VV&A) process. The guidelines established for the VV&A process include: (1) SASS output comparisons with real-world data produced from static range measurements and flight tests; and (2) Touchstone / simulation comparisons. The touchstone model chosen for SASS comparisons is Xpatch Comparisons with, real world, and other models (such as Xpatch) have been used as a means of validation. However, because of the security classification nature of these analysis, we will not show these results.

Figure 4.a shows a typical synthetic HRR PP signature produced by SASS. In this case, the generic RV shown in Figure 3.a was used for demonstration. The center frequency is $10GHz$, and the bandwidth is equal to $4GHZ$. The frequency step is $\Delta f = 35MHz$. The generic RV is $1.75m$ long, with base radius equal to $0.57m$. The nose diameter is $0.26m$. Figure 4.b shows the corresponding OP signature.

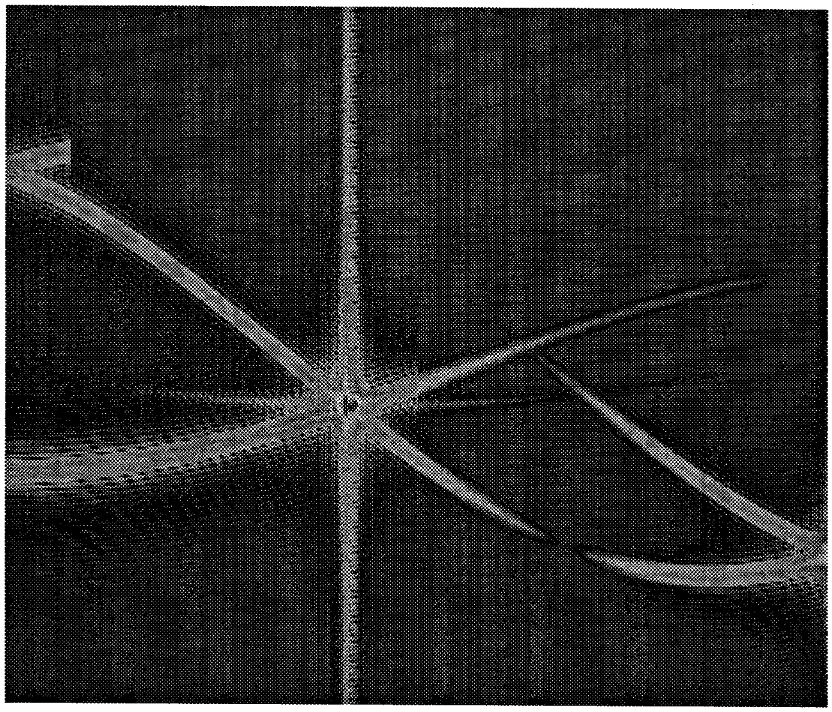


Figure 4.a

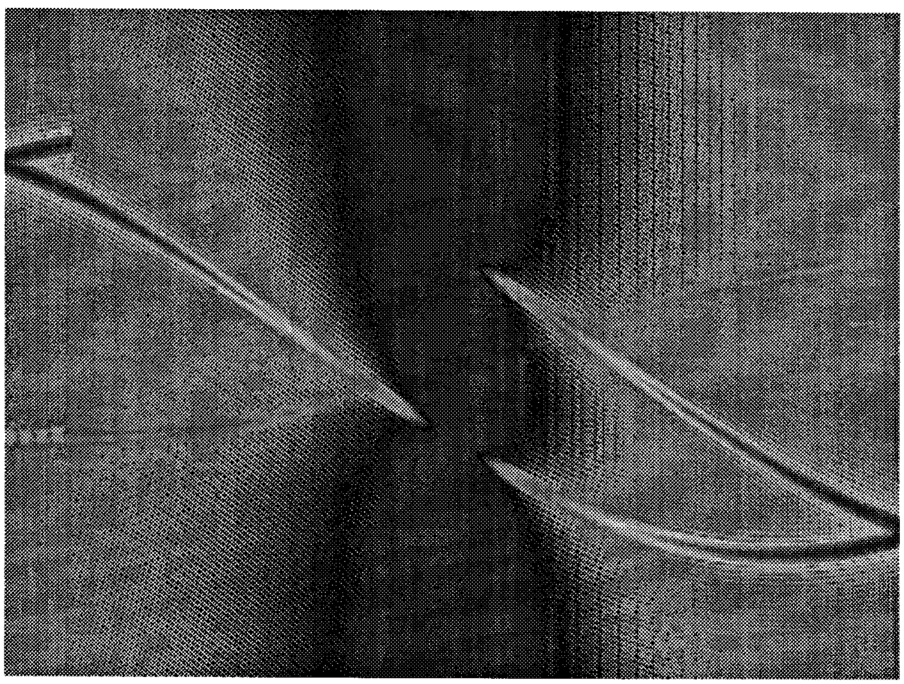


Figure 4.b

V. Conclusions

A very fast running simulation, entitled Sensor and Signature Simulation (SASS) was developed, validated, verified, and utilized for use within the NMD GBR HWIL test-bed, as a means for radar RCS and target signature generation. Narrow band, wide band target signatures are only two of the many outputs SASS can produce. A synthetic High Range Resolution (HRR) module was also developed and tested. In this case, each of the SFWF sub-pulses is LFM modulated and pulse compressed in order to synthesize the desired target signature. Both PP and OP signatures as well as their respective ratio are calculated and stored in binary format for use with the test-bed. For illustration, a typical sub-set of SASS outputs is presented in this paper.

VI. References

[1]. Bassem Mahafza, Susan Campbell, Todd Worthington, and Antony DiRienzo, "The NMD GBR-P HWIL Testbed - Establishing Requirements for NMD XBR", in *porceeding of the Missile Defense Conference*. Washington D.C.. March 4-5, 1999.

[2]. Crispin, J. W., and A. L. Maffet, " Radar Cross Section Estimation for Simple Shapes", *Proceedings of the IEEE*, Vol. 53, No. 8, August 1965.

[3]. Bassem Mahafza, Stephen Welstead, Dale Champagne, Raj Manandhar, Todd Worthington, and Susan Campbell, "Real-Time Radar Signal Simulation for the Ground Based Radar for National Missile Defense". Presented at the *Radarcon 98, the 1998 IEEE Radar Conference*. May 11-14, 1998.

[4]. Stephen Welstead, Bassem Mahafza, Dale Champagne, Raj Manandhar, and Richard Mullin, "Real-Time Radar Signal Simulation for Theater Missile Defense". Presented at the *43rd TRI Service Radar Symposium*. June 22-23, 1997.

[5]. "*Software Requirements Specification For The Sensor And Signature Simulation (SASS) And The Real-time Sensor And Signature Simulation (RT-SASS) Of The Theater High Altitude Area Defense Radar Testbed*", Internal technical Report, Colsa Corporation, 1996.

[6]. Bassem Mahafza, "*Introduction to Radar Analysis*", CRC Press, 1998.

[7]. Donald Wehner, "*High Resolution Radar*", Artech House, 1987.

[8]. James Scheer, and James Kurtz, Editors, "*Coherent Radar Performance Estimation*", Artech House, 1993

CHEMICAL COMPOSITION AND TOXICITY ASSESSMENT OF PYROTECHNIC OBSCURANT MUNITIONS

DERA/WSS/WS5/SP990230/1.0

Ian Welford, Grahame W Poulson, Peter J D Collins, Colin J Hutchinson

Defence Evaluation & Research Agency
Fort Halstead
Sevenoaks, Kent
United Kingdom
Tel: [44] 1959 515348
Fax: [44] 1959 516065

ABSTRACT

The procedures to assess the toxicological and environmental impact of pyrotechnic obscurant munitions requires detailed knowledge on the mass and distribution of the chemical species produced, in order to comply with national, and international laws. This paper will describe the various techniques the UK are assembling to assess obscurant pyrotechnic munitions.

The chemical species generated in the by-products of combustion and those found in the residue following ignition, are determined by controlled laboratory tests. Combustion of the pyrotechnic composition is performed within a Parr bomb chamber, with an air atmosphere pressurised to 10^6Pa. The resultant chemical species are analysed using a combination of thermogravimetry - FTIR analysis, thermal desorption/gas chromatography/mass spectrometry, and aqueous extraction techniques. The probabilistic field trial concentration and dosages during dissemination of the obscurant screen are determined as a function of meteorological conditions and topography using the computer program SCIPUFF. Any hazard to personnel can then be assessed by comparison with exposure limits published by the UK Health and Safety Executive. The description of these analytical techniques will be illustrated by examples from the recent assessment of the L84A1 hand thrown smoke grenade.

1. INTRODUCTION

Historically, military smokes and pyrotechnics have not been subject to any statutory regulation relating to their toxicity. In view of the recognition by the UK MoD of its duty of care in health, safety and environmental issues, future procurements of obscurant munitions will be required to address these issues. To this end, a set of toxicity testing guidelines were drawn up in 1988, and subsequently revised in 1996 [1]. The revisions took into account technological advances in munition design and importantly gave consideration to the context in which the munition is to be used, distinguishing between training or operational use. The revised guidelines have been proposed to NATO and currently form the basis of future UK assessment methodology.

This paper describes the revised guidelines and the development work undertaken in support of their practical implementation. This is illustrated by means of an example, taken from the recently considered assessment of the L84A1 hand thrown smoke grenade.

It must be emphasised that the results from this study relating to the inhalation hazard from the L84A1 are subject to ratification by the UK medical/toxicological authority.

2. TOXICITY TESTING GUIDELINES

According to the revised guidelines for toxicity testing of smokes and pyrotechnic mixtures [1], the most significant toxicology aspect relates to the inhalation of the airborne components. It also states that a lesser threat is posed by cutaneous and ocular routes of exposure. In addition, environmental issues need to be considered, such as the surface deposition of chemical species leading to the poisoning of flora and fauna and contamination of water sources. However, the scope of this paper is limited to exposure via inhalation.

The assessment guidelines can be broken down into the following discrete stages:

Identification and quantification of airborne species: This can be estimated from knowledge of the composition and prediction of likely chemical reactions. However, the preferred approach is to identify and measure each species within the smoke cloud directly, by chemical analysis.

Determination of safe exposure limits: An exposure limit will be a function of factors such as frequency and duration of exposure (for example, single exposure will have a different limit to multiple long term exposures). Therefore, the proposed method of use of the obscurant munition must first be reviewed as this will input into the selection of an appropriate safety limit. To this end, the toxicity guidelines draw parallels with workplace exposure to chemical guidelines and recommend that Government specified Occupational Exposure Limits (OELs) are used as the source of exposure limits.

Determination of exposure to each chemical species: To determine exposure, the atmospheric dispersion of the obscurant cloud under a range of meteorological conditions needs to be considered. To physically conduct such assessments under a range of meteorological conditions is impractical, therefore some form of prediction must be substituted.

3. L84A1 HAND THROWN SMOKE GRENADE

The L84A1 hand thrown smoke grenade (figure 1) is in service with the British Army. The grenade contains red phosphorous as the smoke producing composition, with a payload mass of approximately 225g. The grenade is of conventional design with twist and pull safety pin and fly off lever operating a percussion ignition train. Operation is by removal of the safety pin and throwing to the location where the smoke is required. Subsequent initiation of the central burster charge disseminates the payload over an area of approximately 5m radius, giving a typical screen duration of 30 seconds. The active ingredient, in terms of screen effectiveness, is phosphoric acid (H_3PO_4), formed on the reaction between phosphorus pentoxide and moisture in the atmosphere. Therefore, humidity will affect the performance of the munition, and the safety distance.

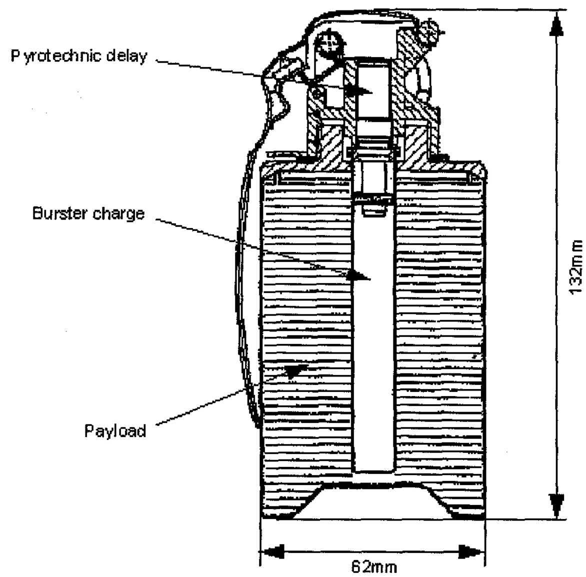


Figure 1 - L84A1 hand thrown smoke grenade

4. CHEMICAL COMPOSITION OF SMOKE CLOUD

The approach adopted in identifying and quantifying the chemical species, was by means of direct analysis of the resultant smoke cloud. Combustion of the pyrotechnic composition and containment of the resultant by-products was performed in a Parr bomb chamber [2]. After allowing the aerosol to condense, the products of reaction were collected by purging through Tenax adsorption tubes and analysed using a thermal desorption – gas chromatography – mass spectrometry technique. The condensed aerosols were collected by washing with water, and the resulting solutions were analysed using ion chromatography and direct current plasma spectrophotometry. Combustion was also carried out using thermogravimetry – Fourier transform infrared spectroscopy, to examine weight loss and to identify the major constituent of the smoke aerosols.

In total, 34 chemical species were identified. Table 1 contains a subset of the data, namely the three most abundant and the two least abundant species identified.

Chemical species	Mass
Phosphoric acid	338g
Hydrogen chloride	10g
Benzene	13.7μg
Butene	0.007μg
Butdiyne	0.004μg

Table 1 – Most and least abundant airborne products of L84A1

5. HEALTH AND SAFETY DATA

The toxicity testing guidelines recommend the use of work place occupational exposure limits (OELs) for chemicals as the basis for the safety assessment. For the purposes of this assessment, the health and safety data was extracted from [3].

[3] details exposure limits for the majority of the species identified in the analysis of the L84A1. This is given in terms of either the Short Term Exposure Limit (STEL), or the Time Weighted Average (TWA). The STEL concentration, is the specified concentration limit that can be tolerated for a time interval of 15 minutes and the TWA concentration is the concentration limit permitted for a period of 8 hours. In order that comparisons with the safety limits can be made, each of these concentration limits need to be transformed to a dosage, as this takes into account both concentration and duration of exposure. The following example considers how to make such a comparison.

The dosage D experienced at a given point (x,y,z) is defined as follows;

$$D(x,y,z) = \int_{screen\_duration} c(x,y,z,t).dt \qquad (1)$$

where c is the mass concentration at the point (x,y,z) and t is time.

The STEL is the concentration permitted for 15 minutes, therefore the dosage exposure limit, D_{STEL}, is given by;

$$D_{STEL} = C_{STEL} \,.\, 15 \text{ minutes} \qquad (2)$$

where C_{STEL} represents the STEL concentration limit.

The dosage D, at any point can thus be compared with the exposure limit dosage D_{STEL} determined above, in order to make a safety assessment.

Table 2 contains information on the three most abundant chemical species produced from the combustion of the L84A1 grenade. For each species, the OEL data (either STEL or TWA concentration limit) and an estimated concentration (assuming that the total mass of that species were produced instantly and uniformly distributed throughout a sphere of 1m radius) are given. The estimated concentration is indicative of the maximum likely concentration levels that might be experienced in the vicinity of the event. This value is an upper estimate for concentration as the payload will be dispersed over a disc on the ground, typically of radius 5m. Furthermore, the payload will burn for a given duration, whereas this calculation assumes that all the screening material is produced instantly. The use of this worst case scenario ensures that no potentially hazardous species were ignored. This process was completed for all the chemical species identified, although only the three most abundant species are shown in table 2.

Species	**Mass**	**OEL mg/m^3**	**Estimated Initial concentration mg/m^3**
Phosphoric acid	338g	2 (STEL)	8×10^4
Hydrogen chloride	10g	7.6 (STEL)	2×10^3
Benzene	13.7μg	16 (TWA)	3×10^{-3}

Table 2 – Concentration of the most abundant species produced by the L84A1

By comparison of the estimated initial concentration with the OEL figure, it is possible to rank the species in order of the hazard they pose. Any chemical species whose likely maximum concentration is orders of magnitude lower than the threshold OEL concentration can be neglected from further consideration. Any species whose maximum concentration is similar, or greater, than the limiting threshold must be considered further. This is justified

on the grounds that any controls set in place to safeguard against the greatest threats will necessarily give protection against the lesser threats.

From table 2, it can be seen that the overall assessment problem reduces to investigating two species, namely phosphoric acid and hydrogen chloride, as these are the only products with estimated concentrations greater that the appropriate STEL limit. The problem can be reduced further because not only is phosphoric acid present in greater quantities than hydrogen chloride, it is also subject to a lower OEL. Thus controls set in place for phosphoric acid will necessarily be sufficient for hydrogen chloride.

According to [3], for phosphoric acid;

$$C_{STEL} = 2 \text{ mg.m}^{-3} \tag{3}$$

Thus the STEL dosage limit for phosphoric acid can be calculated according to equation 2;

$$D_{STEL} = 0.0018 \text{ kg.m}^{-3}\text{.s} \tag{4}$$

It is worth noting that the actual values chosen for safe exposure limits will depend on the proposed mode of use of the munition. However, once concentration/dosage maps have been generated, the variation of safety distance with exposure limit and mode of operation can be explored. The scope of this paper purely considers safety in accordance with the STEL threshold.

6. ATMOSPHERIC TRANSPORT

The previous section determined the concentration and dosage limits for the primary inhalation hazard, which was shown to be phosphoric acid. To physically conduct a toxicological assessment for the range of meteorological conditions in which the munition will be used is impractical. Therefore, to assess the dispersion of the hazardous species the use of numerical simulation is invoked, namely the SCIPUFF model.

SCIPUFF (Second Order Closure Integrated PUFF) is a Lagrangian transport and diffusion model. This model is a component of the Hazard Prediction and Assessment Capability (HPAC) developed by the Defense Threat Reduction Agency (DTRA) of the US. HPAC is primarily designed for the hazard assessment of nuclear, chemical and biological incidents and is claimed to be good for 'nearly any' atmospheric incident. Chemical, biological and nuclear materials can be hazardous in extremely low concentrations, thus the model is designed to predict atmospheric transport from releases over large time intervals and distances (i.e. several hours and hundreds of km's). Although the assessment of the L84A1 grenade has been reduced to predicting the dispersion of a single species, SCIPUFF is equally capable of modelling the combined effect of many components when no single species is dominant.

SCIPUFF facilitates input of a comprehensive range of scenario description parameters, while its fundamental output is a 3 dimensional, temporally variant concentration map. Integrating throughout the screen duration, dosage at any point can be determined. The output also incorporates a probabilistic component to account for random atmospheric fluctuations. The UK executed a series of field trials to confirm the validity of the application of SCIPUFF to this short range domain.

A safety assessment is made by inspection of the downwind dosage variation. Based on toxicological considerations, the minimum safe distance from the detonation point is where D(x,y,z) is equal to D_{STEL}. At this point the dosage received is at the limit and therefore only one such exposure could be tolerated. Moving further downwind, the dosage decreases, therefore a number of such exposures as given by $D_{STEL}/D(x,y,z)$ may be tolerated. This type of analysis would be used to determine a safe distance for a trainer who may have to be present at many such incidents, although as the dosages become lower a more appropriate limit may be selected such as the TWA.

To quantify the hazards from a single grenade, simulations were carried for a number of meteorological conditions. The range of conditions encountered considered variations in wind speed and atmospheric stability. The grenade was approximated to a point source evolving the airborne products uniformly for 30 seconds from ground level.

The following figures relate to the dispersion of phosphoric acid at a height of 1.8m for moderate weather conditions; namely a wind speed of 4.1ms^{-1} (along the x axis) and neutral stability conditions. Figure 2 shows the mean H_3PO_4 concentration map corresponding to 120 seconds after detonation of the grenade. (Note: the black triangle represents the detonation point.)

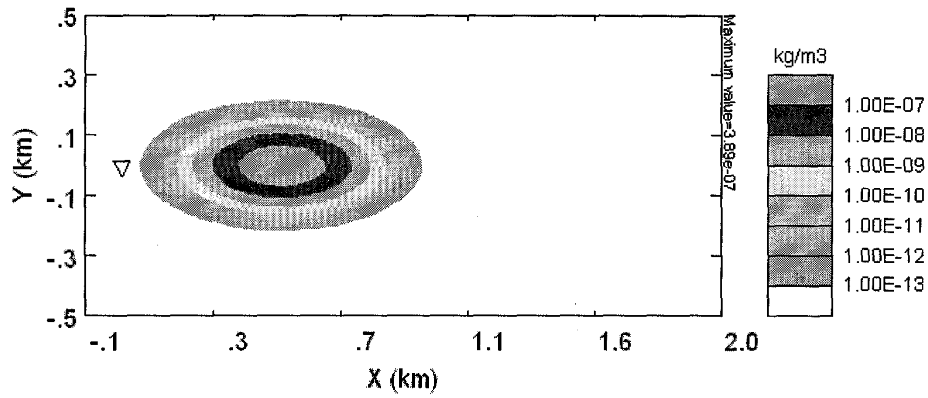


Figure 2 – Mean H_3PO_4 concentration map at t=120 seconds

Integrating over the duration of the screen, figure 3 is the phosphoric acid dosage map, with an automatic scaling of the contour levels.

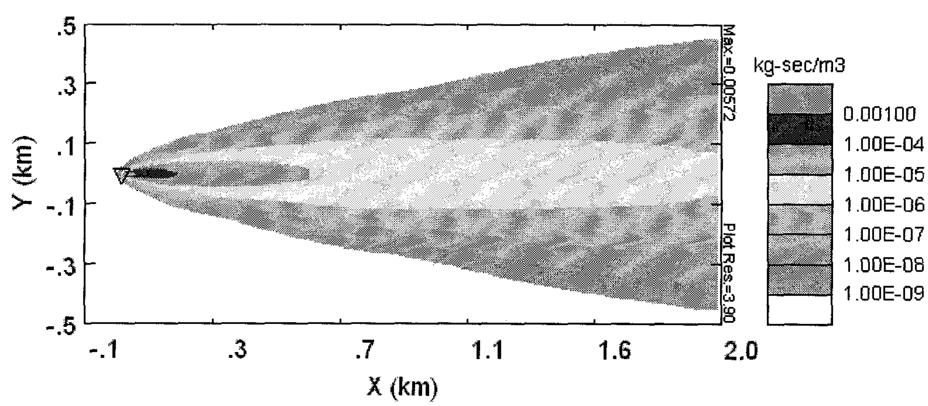


Figure 3 –H_3PO_4 dosage map (autoscale)

Figure 4 presents the same data set as figure 3, but on an expanded scale and with a single threshold level set equal to D_{STEL}. Therefore, the shaded area of figure 4 indicates where the exposure safety limit is exceeded.

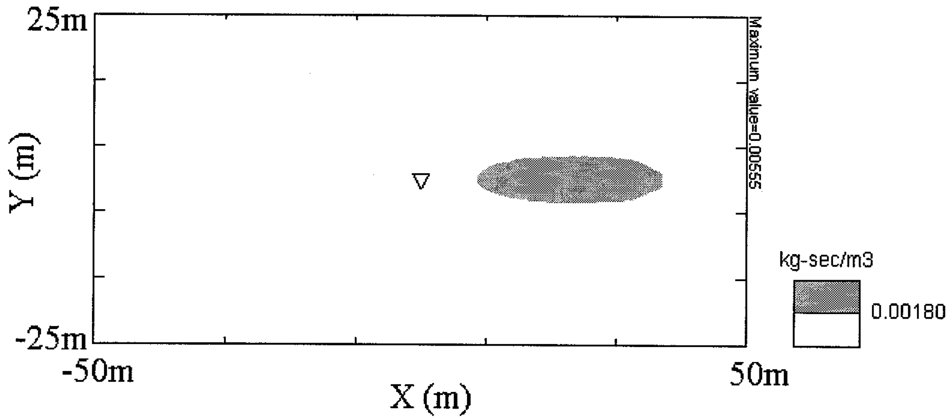


Figure 4 – H_3PO_4 dosage map (single threshold equal to D_{STEL})

7. DISCUSSION

This report has outlined the UK toxicological hazard assessment techniques, using the L84A1 hand thrown smoke grenade as an example.

The first stage of the assessment requires identification and quantification of all airborne products of combustion. This was achieved by direct analysis of the smoke cloud using a Parr bomb system to contain all the products of combustion. A total of 34 species were identified as airborne products of combustion. Two species were found to be dominant, namely H_3PO_4 and HCl, although this in itself is not grounds neglecting the other species. In order to reduce the number of species to be considered, an estimation of initial concentration was made, and compared with the corresponding OEL. Any species whose estimated concentration was significantly less than the OEL was neglected from further consideration. The results of this technique highlighted than H_3PO_4 was the primary threat and that controls set in place for this would be sufficient to protect against the other chemicals identified.

SCIPUFF was used to model the atmospheric transport of H_3PO_4, under a range of atmospheric conditions. Variations in atmospheric stability and wind speed were shown to have significant effect on safety templates, As an example of this assessment, figures relating to a wind speed of $4.1ms^{-1}$ with neutral atmospheric stability were presented. Figure 4 shows that under these conditions the minimum safe downwind distance in relation the inhalation of the airborne products is approximately 35m. At this distance only one exposure could be tolerated. However, if more exposures were expected, the dosages maps could yield the distance at which a number of munitions could be tolerated (although, this would not necessarily use the same OEL threshold).

An assessment structured along the guidelines outlined in this paper will help in the development of procedures to control the risk, by the use of appropriate personal protective equipment and restrictions/guidelines on usage.

It must be emphasised that interpretation of the inhalation assessment of the L84A1 hand thrown smoke grenade is subject to ratification by the UK medical/toxicological authority.

8. CONCLUSIONS

This paper has demonstrated how the UK use a combination of laboratory analysis techniques and numerical simulation methods, in conjunction with OELs, as the foundation of a toxicological hazard assessment process for obscurant munitions. The end product of this process is a series of safety templates, such that the exposure thresholds are not exceeded for a range of likely meteorological conditions. In conducting such an assessment, consideration needs to be given to the following areas:

- Personnel to be exposed (military or civilian)
- Number/frequency of exposures (trainer v trainee)
- Political circumstance (regular occurrence or 'one off')

The issues raised by these topics will effect the chosen safety limit, for e.g. STEL or TWA. Depending on the current political climate and the proposed region of use, consideration of the various circumstances listed above, may determine that the published occupational exposure limits are not the most appropriate threshold to determine the safe operating conditions relating to the use of obscurant systems. However, even in such a case, the process would remain the same and would simply require substitution of the appropriate limiting dosage threshold.

Once the inhalation risk has been considered, other hazards to personnel and the environmental issues need to be considered, in order to complete the toxicological and environmental impact assessment.

9. REFERENCES

[1] RICE P., *Guidelines for toxicity testing of smokes and pyrotechnic mixtures*, DERA/CBD/MC/CR96026/1.0, September 1996.

[2] GUPTA M. L., HUTCHINSON C. J., MERCER A. J., NORRIS V. J., Chemical analysis of smoke aerosols and residues, *The Smoke/Obscurants Symposium XX*, 28-30 April 1998.

[3] Health and Safety Executive (HSE*), Occupational Exposure Limits. Guidance Note EH40/98*, 1998.

A Structured Design & Analysis Methodology for Guided Weapon Concepts

By Michael R. Vanden-Heuvel
and Rebecca L. Lenz

Air Force Research Laboratory/Munitions Directorate (AFRL/MNGG)
Eglin Air Force Base, FL 32542 USA

JAWS Track: Acquisition Initiatives

Abstract

Formulating and analyzing guided weapon concepts to meet user needs is both an art and a science. Choices made for certain subsystems impact the selection and design of other subsystems, dictating the need for an integrated approach. It is clear that the sequence and method used for model development or modification must be carefully chosen to account for subsystem interaction in order to minimize subsystem model redesign. Additionally, optimal choice of simulation runs is important during the concept formulation phase as well as during the final evaluation phase for weapon concept comparisons to best aid the selection and adjustment of design parameters.

A methodology has been developed for guided weapon concept formulation, modeling, and analysis. The perspective is from the standpoint of a government laboratory that is developing new guided munition technology. The focus is not on detailed weapon design, but rather on high-level concept design, that allows comparison and selection of one or more concepts for a more detailed design later. The methodology addresses the functional interaction of all weapon subsystems and follows a sequential design. The result is a non-optimal, but highly useful solution, which looks at concept viability. The methodology also addresses simulation-generated data used in the design process and in the ultimate analysis process to compare performance with user requirements.

1. Introduction

At the Air Force Research Laboratory's Munitions Directorate, located at Eglin AFB, Florida, the Guidance Simulation Branch of the Advanced Guidance Division (AFRL/MNGG) is responsible for analyzing the effect of evolving laboratory technologies on the performance of existing and conceptual air-launched guided munitions. Simulation development at AFRL/MNGG is accomplished using the recently developed MSTARS (Munition Simulation Tools and Resources) Simulation System[1], a

[1] For more information on MSTARS, contact Mr. Scott Hess at (850) 882-8195 ext. 3282 or hessjs@eglin.af.mil.

visual simulation environment, which contains a repository of munition component models. The visual environment and the repository perfectly suit the needs of AFRL/MNGG because they enable simulations to be developed rapidly based on prototype system components that can be modified as needed to meet customer requirements. Additionally, the visual environment provides an intuitive feel of how the simulation components work together. Figure 1 shows the user interface presented at the MSTARS munition diagram level.

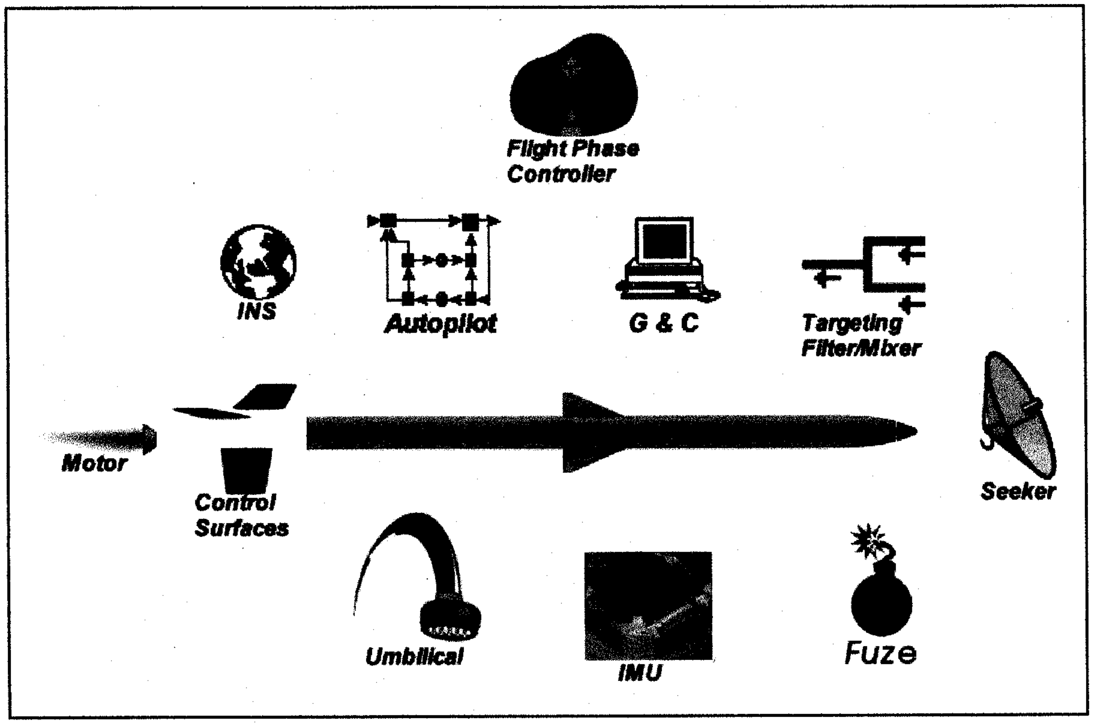


Figure 1. MSTARS Munition Model Components

AFRL/MNGG customers are often working on technologies for use in future weapon systems. Performance requirements for these systems are often vague and incomplete. Such requirements typically include high-level operational requirements such as launch range, and include high-level physical constraints such as weight and size. The vague nature of requirements at this level allows much leeway for design creativity in the simulation process.

Results from a recent in-house concept study[2] performed by AFRL/MNGG indicate that to accomplish successful risk reduction in the formative stages of concept development through simulation, it is necessary to address the simulation development and analysis process from a structured systems approach. There are four key principles inherent in the activities relating to this approach:

[2] Miniaturized Munition Capability (MMC) Analysis of Alternatives (AoA) Concept Study, AAC/DRPW

1. ***Understand the requirement***. The design, development, and integration of simulation models is tightly coupled with the operational requirements and constraints imposed by the warfighter. Therefore, it is necessary to understand all munition operational requirements before any simulation development is initiated.
2. ***Use a structured simulation development methodology***. A well defined, well structured methodology is crucial to building an effective simulation model and to building an efficient, smoothly operating simulation development team. This is true regardless of whether the development environment is visual or code-based.
3. ***Emphasize reusable simulation components***. Simulation development should rely heavily on model reuse and shared data to reduce cost, reduce errors due to building components from scratch, save time, and to prevent model incompatibilities.
4. ***Select analyses appropriate to evaluating critical performance requirements***. Thousands of meaningless simulation runs are no better than zero simulation runs. Only certain high level, but critical, performance characteristics can be evaluated for a conceptual munition. The simulations conducted and the subsequent analyses must be tailored and focused on answering specific questions about the critical performance issues.

In order to put any concept analysis methodology in perspective, it is necessary to understand the "big picture". The problem domain, being addressed here, is the development of munition concepts. The concepts meet user requirements and can be provided to other organizations for further refinement, actual end item development, and production. The elements of the big picture are addressed in Section 2.

Simulation and analysis are critical elements of Munition Concept Exploration process, as described in Section 2. To address these critical elements, AFRL/MNGG has developed a structured approach, making use of in-house tools and a visual simulation system. The methodology is described in Section 3 and embodies the four key principles discussed earlier.

2. The Big Picture

Figure 2 is the authors' depiction of a generic group of activities, which occur from the point where the warfighter defines a requirement through the process of munition concept exploration. The boxes shown in the diagram do not represent any specific DoD, Air Force, or AFRL process. The depiction was created by the authors for convenience to describe generic processes that could represent a number of different situations where concept exploration occurs.

The Munition Concept Development Process is the sequence of activities, resulting in one or more candidate munition concepts. The concepts are provided to a SPO or other organization for final concept selection, development, and production. The overall process is depicted as being comprised of two broad sub-processes: (1) Requirements Definition and (2) Munition Concept Exploration. These two processes have been further divided into a series of sequential overlapping phases, adapted from the well-known Modified Waterfall Model, which allows a return to previous phases if needed. The following sections describe each phase.

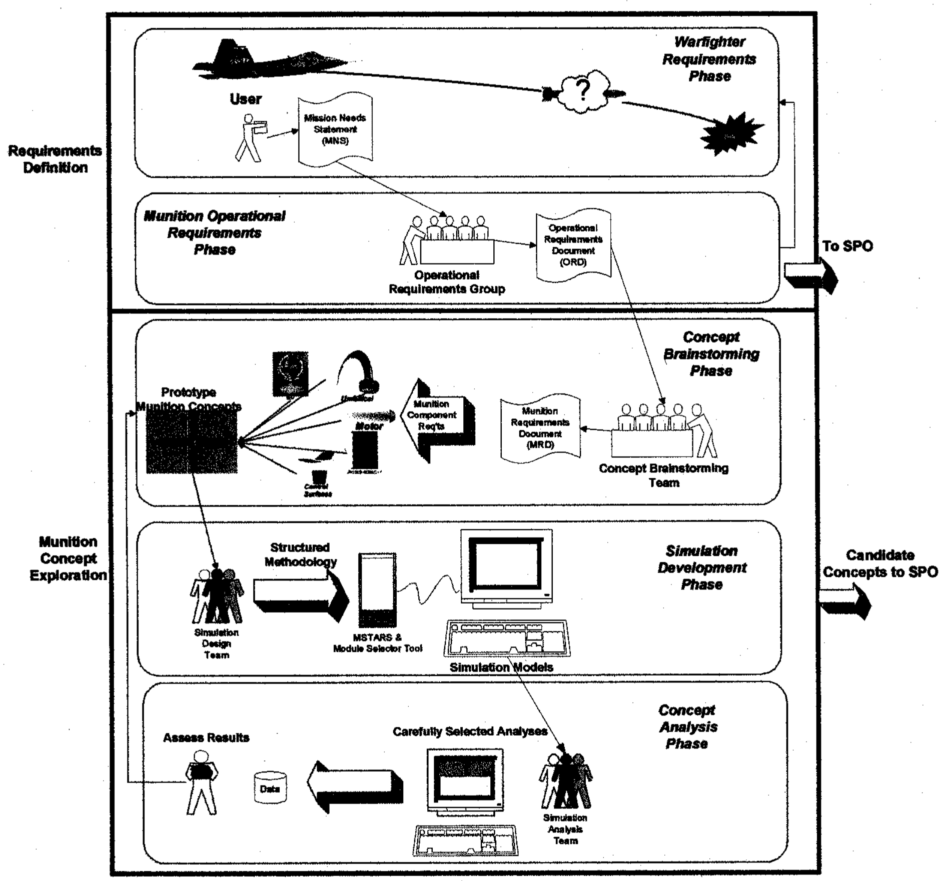


Figure 2. Munition Concept Development Process

2.1 Warfighter Requirements Phase

The Requirements Definition process begins with the Warfighter Requirements Phase, which defines the mission level requirements of the warfighter from launch to impact of the weapon system. This phase takes a problem-oriented approach in describing the mission need in broad terms, as shown in Figure 3. The operational command, the owner of the phase, is continuously evaluating the current weapon systems against the ever-changing threat environment. If the threat changes significantly so that the current systems are unable to counter it with a change in doctrine, tactics, training or organization, then the operational command generates a new requirement, which is specified in a Mission Needs Statement (MNS). A typical MNS may address such areas as:

- Multiple kills per pass
- Multiple ordnance carriage
- Adverse weather capability
- Medium-to-high altitude accuracy
- Capability against hard targets
- Carriage on multiple aircraft
  (e.g. F-15, F-16, F-18, F-117, B-2)
- Increased effectiveness
- Reduced susceptibility to countermeasures

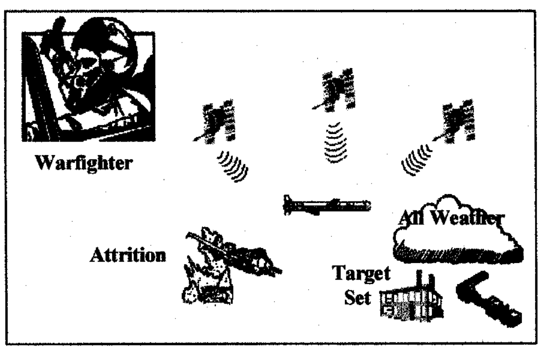


Figure 3. Warfighter Requirements

2.2 Munition Operational Requirements Phase

The warfighter requirements are further refined during the Munition Operational Requirements Phase, which refines the MNS from broad statements into more specific munition operational requirements. This phase is solution-oriented: it describes a detailed approach to solving the warfighter mission needs problem. The Operational Requirements Group, which could be one of several organizations, addresses mission needs from all aspects of operation across the entire life cycle of the system; and is

ultimately responsible for the development of the new munition system. The group must gain a sound understanding of the warfighter needs, to achieve a proper balance between cost, schedule, and performance considerations. The Operational Requirements Group produces the Operational Requirements Document (ORD), which specifies requirements for such things as:

- Aircraft integration issues
- Cost and scheduling
- Survivability
- Effectiveness
- Threats
- Performance
- Logistics
- Mission planning
- Load-outs

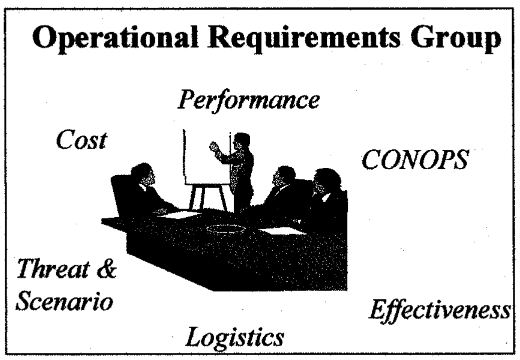


Figure 4. Operational Requirements

The Operational Requirements Group assembles other commands to investigate the issues laid out in the ORD. Sufficient data is collected from the commands so that a recommendation for a new weapon system can be made to the warfighter.

This phase marks the end of the Requirements Definition process. The resulting requirements are extremely important to the subsequent concept formulation and analysis, detailed in Sections 2.3 and 2.4.

2.3 Concept Brainstorming Phase

The Concept Brainstorming Phase marks the beginning of the Munition Concept Exploration process. This process, the main interest of this paper, takes the previously developed requirements and ultimately transforms them into effective candidate munition concepts, which could meet user needs.

The purpose of the Concept Brainstorming Phase is to match munition subsystem design choices against performance requirements, and to eventually identify one or more munition concept prototypes suitable for further study using simulation. The munition operational requirements will impose restrictions on the type of guidance law, autopilot, navigation system, airframe, and propulsion system, which could be selected for use. The Concept Brainstorming Team identifies all applicable technologies (Figure 5), selects those that best suit the requirements, and integrates them to form one or more "paper munitions" that meet the performance requirements. It is desirable that there be several "paper munition" concepts that meet the requirements. Each munition concept is defined in sufficient detail such that the Simulation Development Team, the next players in the process, will have a meaningful starting point for building a simulation of the concept.

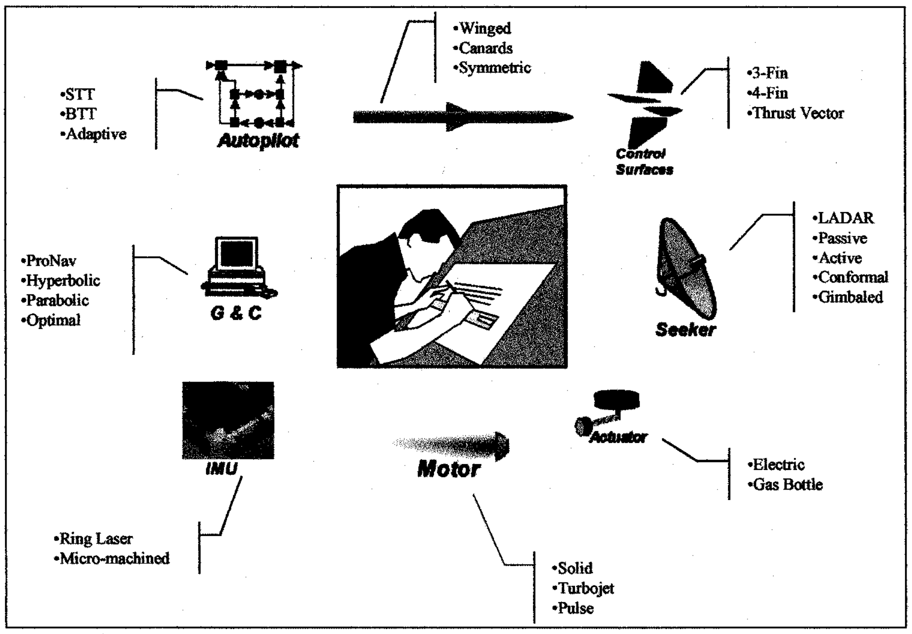


Figure 5. Munition Subsystem Technologies

Although simulation has not been mentioned as a part of this stage, often the paper study is refined with the aid of high level simulation tools, such as three-degree-of-freedom (DOF) simulations. These high level tools aid in verifying preliminary concept design prior to initiating the Simulation Development Phase.

2.4 Simulation Development Phase

In the Simulation Development Phase, the "paper munition" concepts, resulting from the previous phase, serve as the blueprint for the concept simulation models. An organized development approach is used and, in the case for AFRL/MNGG, existing components within the MSTARS library are pulled together to form a prototype. The component models are exchanged and/or modified to satisfy the munition operational requirements. Figure 6 gives an example of a typical simulation and its associated technology components.

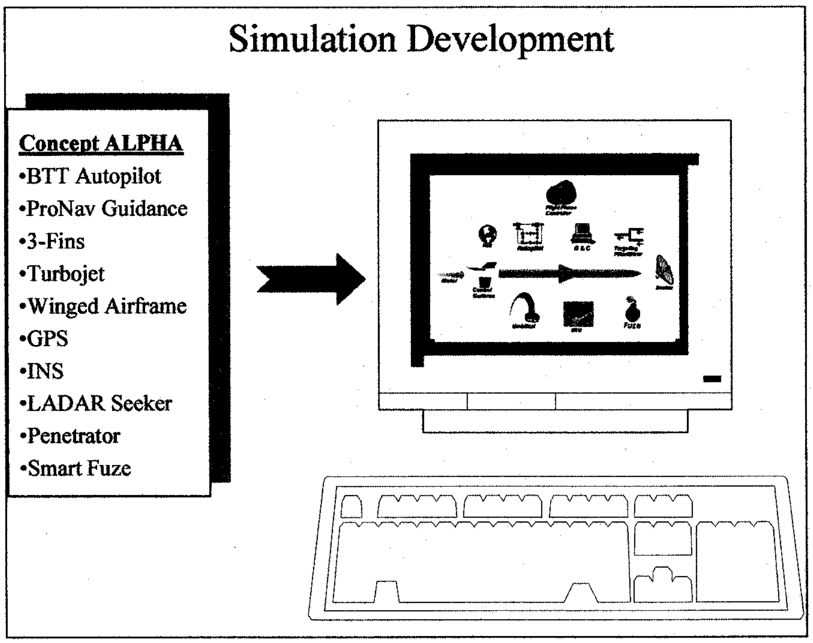


Figure 6. Simulation Development

To improve the effectiveness and efficiency of the simulation development procedure, MNGG has developed a structured methodology, which uses in-house software tools. For each concept, the simulation developed is much more detailed than a 3-DOF simulation, which might have been used in the previous phase. The methodology and the simulation development activities are described in detail in Section 3.1.

2.5 Concept Analysis Phase

The last phase, Concept Analysis, provides an in-depth study of the munition concept performance capabilities. The purpose is to demonstrate the general capabilities of the concept and to verify that critical warfighter requirements have been met. Additionally, comparative simulation results are used to rank the concepts defined by the Concept Brainstorming Team.

It is critical that appropriate analysis objectives be defined, which are keyed to questions about munition performance. Analysis planning, which is initiated in the Simulation Development Phase, is important to determine the requirements for simulation fidelity, identification of analysis data, and simulation functional requirements (such as multi-run capability). More details about this phase are found in Section 3.1.

After preliminary analysis, the Concept Brainstorming Team may find it necessary to correct the original concept specifications due to design errors that were not evident during the Concept Brainstorming Phase. Other concepts may drop out of consideration altogether due to extreme poor performance. The remaining concepts are further evaluated and the results are used to rank the concepts with respect to performance capability relative to the requirements. It should be noted that cost analysis, a critical activity, is conducted during this phase. However, the performance aspect of the analysis process is the focus of this paper.

3. Structured Design and Analysis Methodology

The structured methodology begins during the Concept Brainstorming Phase. The methodology encompasses the four principles discussed in Section 1. The Concept Brainstorming Team (Section 2.3) uses the specifications generated during the Munition Operational Requirements Phase to develop a single, or set of alternative munition concepts. Each requirement will result in some notional ideas from the team regarding subsystem technologies, which could be used to help the munition meet the requirement. Subsystem technology selections may be mutually exclusive or may result in degraded or enhanced performance when used together. Thus, there are many factors to consider. An organized approach is useful to ensure that all critical issues have been considered. Quality Functional Deployment (QFD) or other such approaches can be extremely helpful in determining a meaningful set of concepts.

The MNGG approach does not require any specific technique at this time for generation of the munition concepts. However, the result should be one or more concepts, which are capable (from a gross perspective) of meeting user requirements. Several steps, accomplished during the Concept Brainstorming Phase to arrive at the munition concepts, are repeated in greater detail during the Simulation Development Phase.

Most of the methodology and tools developed by AFRL/MNGG falls in the simulation development and analysis areas. Section 3.1 describes the Simulation Development Approach and Section 3.2 covers the Analysis Approach.

3.1 Simulation Development Approach

The activities described in this section are directly applicable to the Simulation Development Phase described in Section 2.4.

To construct the simulation of a concept, it is useful to look at the munition from both a functional point of view and from an object-oriented point of view.

A functional decomposition of the munition's operational modes separates the primary system functions into successively more detailed processes and defines the data flow between the processes. It provides good visibility into the various critical processes, which occur during weapon flyout. For example, a flight profile for a typical air-to-surface smart weapon can be partitioned into five modes of operation:

- Pre-launch
- Post-launch
- Mid-course
- Pre-terminal
- Terminal

The functions performed during each flight mode are examined to highlight overall simulation requirements and subsystem interaction, based on performance requirements of interest. Analysis of these flight modes can also suggest simulation architecture design decisions, which can make the simulation model more intuitive and effective.

Based on the desired performance analysis to be conducted, a description of data requirements, including inputs and outputs, should be formulated. A description of the data should include the volume and frequency of data to be processed, as well as any specific formats and limitations. These data requirements are critical to the success of the Concept Analysis Phase, discussed in Section 2.5.

An object-oriented view of the simulation, combined with the concept hierarchy, will provide insight into the subsystem model requirements. A Requirements Traceability Matrix (RTM) is produced during the Concept Brainstorming Phase, to ensure that selection of technologies and subsystems relate to the munition requirements. The RTM is further used during simulation development to identify requirements for the munition subsystem models and the simulation architecture.

Building the simulations is greatly aided by using a library of reliable, reusable subsystem model components. The library components, created over years of simulation development, have been through an extensive design, testing, and validation process. The result is a savings in overall design time by maximizing model reuse. The best starting point for a model prototype is a complete, existing, operational munition model, which has the same functional characteristics and many related subsystems as the intended final concept. A top-level description of this process is given in Figure 7.

One of the critical activities that must be accomplished is identification of the subsystems of the model prototype that requires modification in order to meet system requirements. Redesign may not necessarily involve the restructuring of an existing model, but may only require modification of model attribute data, such as aerodynamic or thrust data. In any event, a sequence order for redesign must be established to minimize the need for redesigning subsystem models repeatedly.

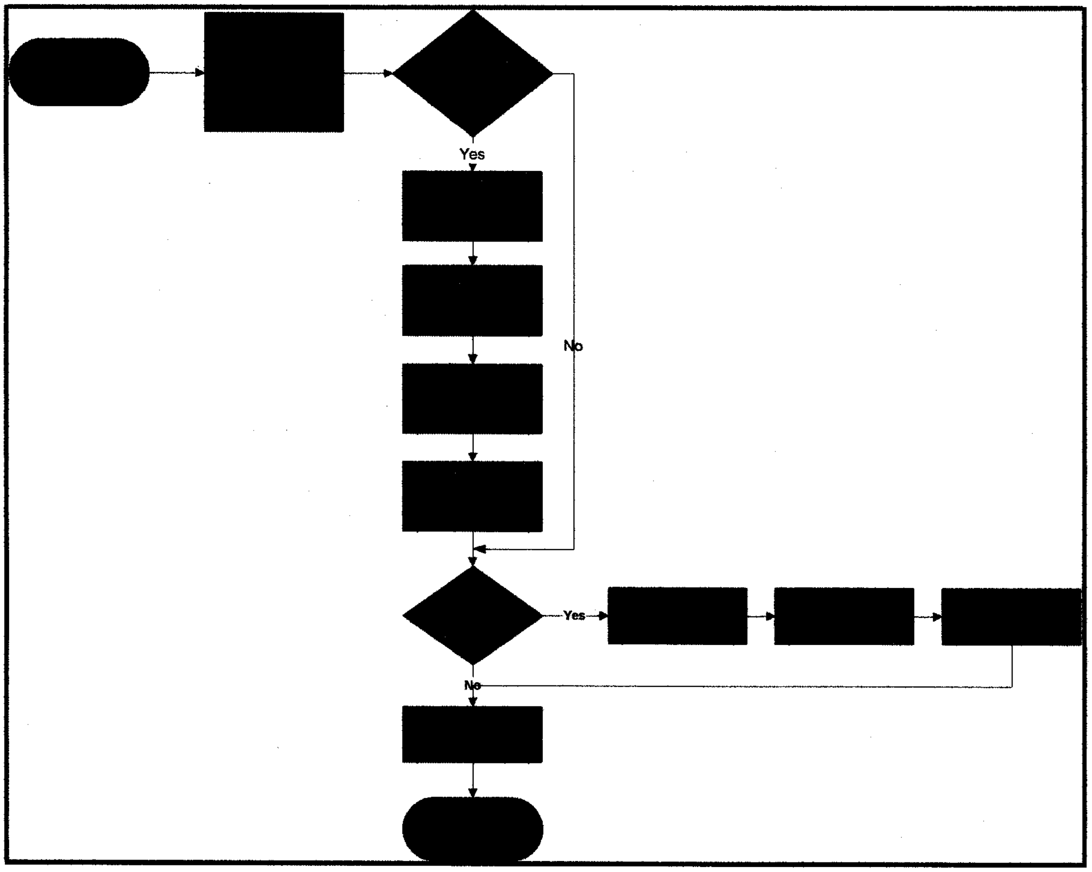


Figure 7. Simulation Development Process

A procedure to determine the subsystem modification sequence has been translated into an AFRL/MNGG in-house software utility called the Module Selector Tool (MST). The MST provides an automated means to establish the optimum sequence order that component modules should be modified. The MST allows the user to select a set of munition subsystem components, specify the components that will require modification, and determine the sequence in which the modifications should occur. It is important to note that the procedure works for a collection of existing models and will not address missing technologies or components. The user may find it necessary to include a "placeholder" for a missing component, ascertain its influences on other components, and then reconfigure the MST.

Figure 8 shows a screen shot of the Module Selector Tool, which consists of four panels: the Module Selector, the Edit Selection, the Dependency Matrix, and the Output panels.

The first user-input panel, the Module Selector (Figure 8), consists of an itemized list of munition subsystem components contained in the MSTARS library. The components are generic enough to allow the user to create a functional prototype munition. The Edit

Selection panel, also a user-input routine, enables the user to specify the components that may require modification in order to meet functional requirements. Associated with each component is a "dependency bin" that sums the effects of modifying dependent components. The logic for determining the dependencies results from a heuristic approach and requires knowledge of the functional dependencies of the models. If a component is selected for modification, then a value of 1 is added to the dependency bin of every component affected by the modification. The tally is used to "weight" the components and to determine the modification order. The higher the number associated with a component, the later in the redesign phase it falls, thus eliminating adverse affects on a previously redesigned component. The components and weights appear in the Output panel as well as on an additional view that provides a sort and a refit schedule.

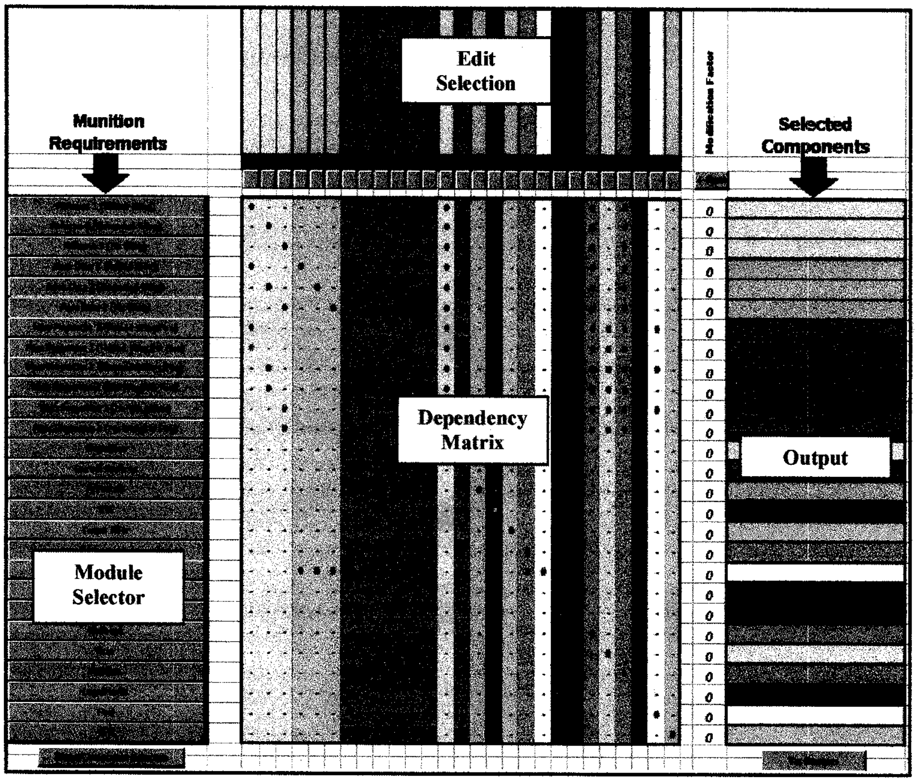


Figure 6. Module Selector Tool (MST) Screenshot

The Dependency Matrix panel is merely a graphical representation of the component dependencies and serves as a sanity check.

When the modification order has been determined, the module modification procedure begins. First, the library component is retrieved from the MSTARS library. The module is customized to reflect the requirements and specifications obtained in the Munition Operational Requirements Phase (this could also be a higher level requirement generated earlier in the overall process). After all changes have been made, an independent reviewer (e.g. another team member) is asked to review the work. The reviewer checks

for errors in design, format, and completeness. This step is necessary because it gives an outside perspective to the work. If no discrepancies were found, the component is passed to another team member for thorough testing. Here, inputs, chosen so that each branch of the module is executed, are fed into the module. The actual outputs are collected and compared against expected outputs to verify that the component is operating correctly. If any discrepancies were found, the module is sent back to the modification step for corrections. The procedure continues until both the modification and testing steps are completed successfully for all components that were marked for change with the MST (refer to Figure 6).

The simulation build process is complete when all modules have been modified and tested, as necessary. The simulation is built by successively interfacing related components. For example, the first step of the build may begin with the guidance computer. The next logical component addition is the autopilot since the outputs of the guidance computer are the inputs to the autopilot. After each new component is added, tests are performed to ensure that the integrated components are working together correctly. This procedure continues until all components have been connected together to form the new munition model.

The last stage of this phase is simulation verification and acceptance testing. The acceptance tests are end-to-end systems level tests and must occur prior to analysis. These tests check the basic functionality of the munition system, such as:

- munition stability
- guidance and navigation accuracy
- propulsion functionality
- other similar functions

If the munition model fails the acceptance tests because of a component implementation error, the component is corrected, tested, and integrated by following the procedure outlined earlier. If the failure is a result of design error, the error is isolated and a re-evaluation by the Concept Brainstorming Team is required.

The end product of the Simulation Development Phase is a set of verified simulations, representing each of the munition prototypes developed by the Concept Brainstorming Team.

3.2 Analysis Approach

The activities described in this section are directly applicable to the Concept Analysis Phase described in Section 2.5. To accomplish the analysis, the simulation is exercised through a series of scenarios, which establish performance boundaries and capabilities.

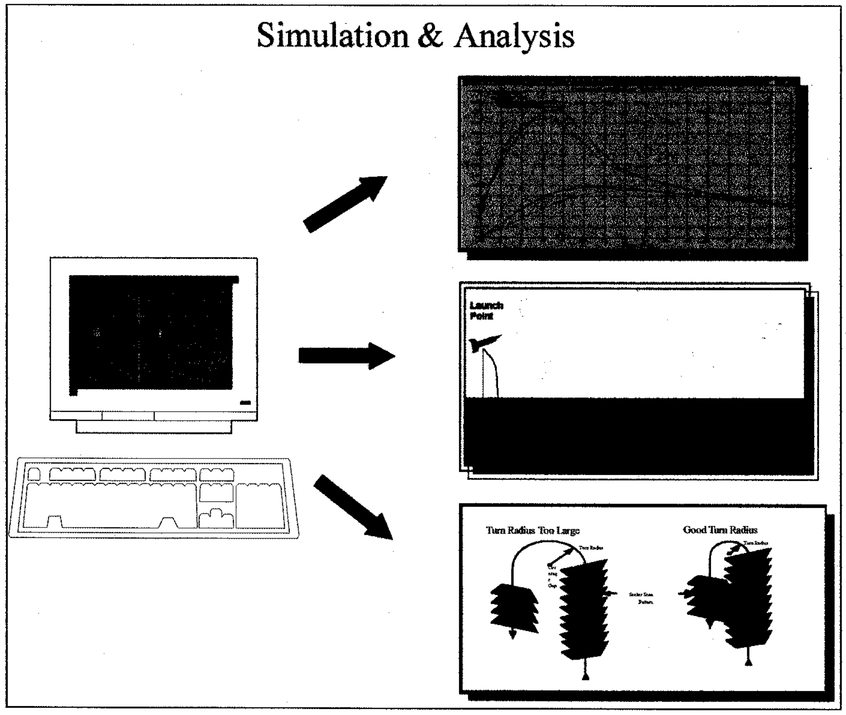


Figure 7. Simulation and Analysis

The areas for analysis must be carefully selected based on the performance criteria, outlined in the ORD. In fact, the performance criteria drive the fidelity and functional requirements of the simulation. For this reason, the identification of the analysis requirements is accomplished during the Simulation Development Phase. Areas for analysis may include:

- munition minimum/maximum range
- maneuver capability
- terminal performance (i.e. impact velocity, impact angle, and miss distance)
- operational environment
- any number of other areas

Based on the initial analysis data, additional analysis may be required to perform trade-off studies, which address particular system components and their impact on overall

performance. The trade-off studies provide information for risk reduction, technology investment decisions, and serve to refine the concept.

All performance data generated from the simulation and analysis effort is collected and compiled by the Operational Requirements Group. The data is used to reject unacceptable concepts. The final refined concepts and performance analysis results are typically provided to a SPO, or similar organization, for use in selecting one or more concepts for possible development and production.

4. Conclusion

For convenience and clarity, MNGG has depicted the overall concept development process as consisting of two sub-processes: (1) Requirements Definition and (2) Munition Concept Exploration. Activities occurring in the two processes have been mapped into five phases. Concept Exploration has three phases, and it is in the latter two phases, involving simulation and analysis, where MNGG has developed an organized methodology and in-house tools to make the activities more efficient and effective.

The various activities of the simulation and analysis methodology employed by MNGG embody four key principles:

- ***Understand the requirement.***
- ***Use a structured simulation development methodology.***
- ***Emphasize reusable simulation components.***
- ***Select analyses appropriate to evaluating critical performance requirements.***

In the course of developing the methodology, MNGG has developed in-house software tools, which aid in making the simulation development and analysis more effective. These include:

- ***The MSTARS Simulation System***
- ***The Module Selector Tool (MST)***

The methodology and tools were developed during a recent major effort to analyze a set of munition concepts. Since that effort, the methodology and tools have been further refined and are continuing to evolve. Practicing such a methodology and using effective tools can tremendously reduce the time required to conduct munition concept analysis and can make that analysis much more effective.

Using 6-DOF Simulation to Determine Acquisition Requirements for Advanced Staring LADAR Focal Plane Array

(Approved For Public Release May 26, 1999 – Case # 99-169)

Craig M. Ewing

Air Force Research Laboratory/Munitions Directorate
101 West Eglin Blvd., Suite 304
Eglin Air Force Base, FL 32542
ewingc@eglin.af.mil

Abstract

The need for "smart" munitions that minimize collateral damage and maximize the number of kills per sortie has prompted the Air Force to investigate the use of onboard seekers to increase weapon accuracy. One seeker currently under consideration is a staring focal plane array LADAR ("flash" LADAR). Before beginning an acquisition program for the flash LADAR, analysis to examine its feasibility and determine preliminary performance requirements was desired. This paper discusses the simulation environment, methodology, and results of the analysis.

Introduction

The mission of attacking both high-value fixed and moving targets through the use of a small smart bomb (SSB) is currently under consideration by the Air Force. A typical scenario for a direct attack mode of the SSB may consist of: launch from a standoff distance of over 40 miles; non-powered, wing-assisted glide into target area; pitch-over to achieve maximum impact velocity; and finally acquisition of the target by a terminal seeker.

Two important requirements for flash LADAR seeker feasibility are update rate and field-of-view (FOV). Update rate is defined as the rate at which the seeker and signal processor can give a target location measurement to the terminal filter. FOV is the instantaneous angle seen by the staring focal plane seeker. Monte Carlo analysis against both fixed and maneuvering targets was performed. The maneuvering target represented a missile launcher performing an emergency-braking maneuver. A 6-DOF simulation representing a SSB mission against these two targets was rapidly developed using an in-house modular simulation tools and resources (MSTARS) methodology.

MSTARS is a visual simulation environment using the product VisSim as the programming language. Munition components are developed and maintained in a modular environment that enables rapid integration of subsystem models into the MSTARS simulation architecture. Using this system, a simulation modeling the flash LADAR seeker on a SSB was put together in a matter of a few days.

While global positioning system (GPS) measurements are assumed available to the SSB, a jammed GPS environment was used for comparison purposes. Other error sources included typical target location error (TLE), inertial measurement unit (IMU) noise, and seeker noise. The next section discusses the engagement scenario and simulation parameters that were used in the analysis.

Engagement Scenario

There were two types of engagement scenarios under consideration. The first was a high-value fixed target (HVFT), while the second consisted of a missile launcher performing a decelerating, braking maneuver during the last few seconds of the engagement. To save simulation time, no large standoff range was used for this analysis. In both scenarios the target was initially located at 20 km downrange from the munition launch point with no cross-range location. The munition was launched using the simulation conditions given in Table 1.

TABLE –1
Launch and Noise Conditions

Parameters	(units)	Unjammed	Jammed (~75 sec)
Launch Altitude	(ft)	40,000	Unchanged
Launch Velocity	(Mach)	0.8	Unchanged
Seeker Acquisition Range	(m)	1500	Unchanged
Seeker Blind Range	(m)	200	Unchanged
Desired Impact Angle	(deg)	85	Unchanged
Seeker Range Error	(m)	0.5	Unchanged
Seeker Range Rate Error	(m/s)	0.05	Unchanged
Seeker Angular Error	(rad)	0.00067	Unchanged

A single initial 6-DOF fly-out to seeker acquisition range was completed using no noise or error sources and the true target location. The munition end-state conditions for the seeker acquisition point were saved and used to initialize all future runs. The statistical errors associated with a typical GPS inertial navigation system (INS), as well as TLE were added to the true target location to simulate the errors that would have built up over the fly-out. This saved numerous hours of simulation time and allowed the study to be completed in less than two weeks.

The SSB was modeled as a 250-pound guided munition. It is shown in Figure 1 compared with a conventional 2000-pound munition. The munition guidance system used against the maneuvering target consisted of a terminal seeker, extended Kalman filter (EKF), optimal

guidance law, and aero-adaptive autopilot. The terminal seeker measured range, range-rate, azimuth, and elevation. These measurements were then sent to the EKF at various update rates to produce state estimates at 100-hertz (Hz) for the guidance system. Guidance commands were generated and transferred to the autopilot where they were turned into three fin deflection commands. In the case of the HVFT mission, no EKF was used and the seeker measurements were used directly in a proportional navigation guidance law.

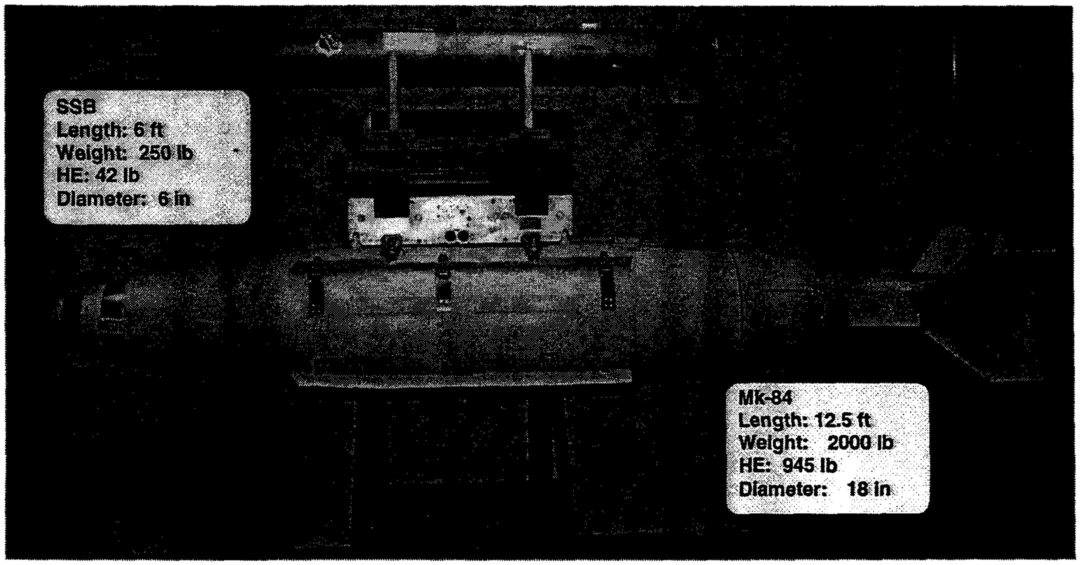


Figure 1. Comparison of SSB with Mk-84

In the HVFT scenario, the target's location was assumed known to within a typical target location error (TLE). Beginning with the previously saved seeker-acquisition end-state conditions, the SSB was flown against the HVFT. Each run set consisted of 31 Monte Carlo runs for each set of conditions. TLE and GPS errors were root-sum-squared (RSS'd) and added to the true target location at the beginning of each Monte Carlo run. This is equivalent to the error in target location that would be seen by the seeker upon acquisition in a full fly-out scenario. Figure 2 shows the target position errors upon seeker acquisition for both the jammed and unjammed scenarios. The seeker update rates used were 100, 50, 20, 5, and 1 Hz, along with a one-look only case.

The maneuvering target case was slightly more complicated. Again the target's initial location was assumed known to within a typical TLE. However, in this scenario the target was given an initial unknown downrange velocity of 15 m/sec at the start of seeker acquisition. It immediately slammed on its brakes to decelerate to zero velocity during the terminal engagement, posing a stressing guidance problem.

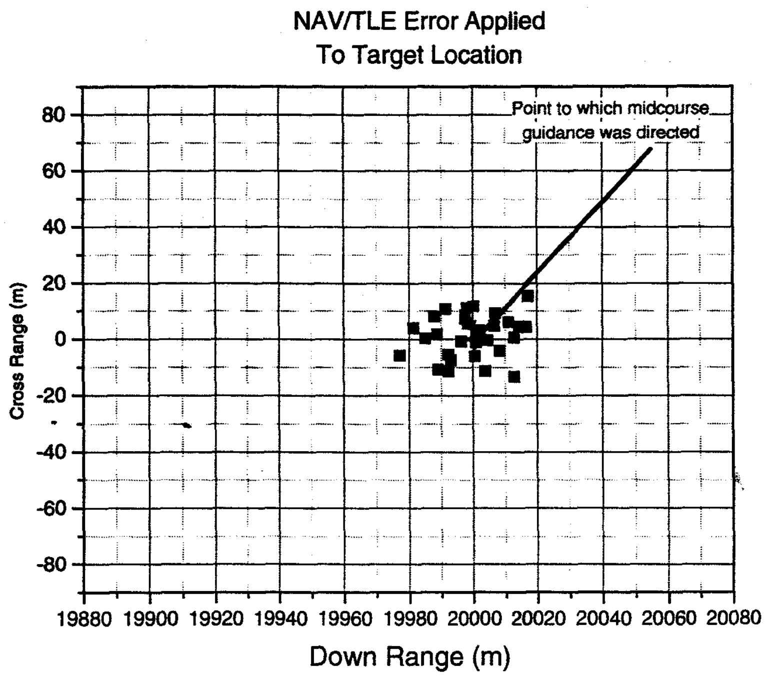


Figure 2a. Unjammed target locations seen by seeker
At start of acquisition

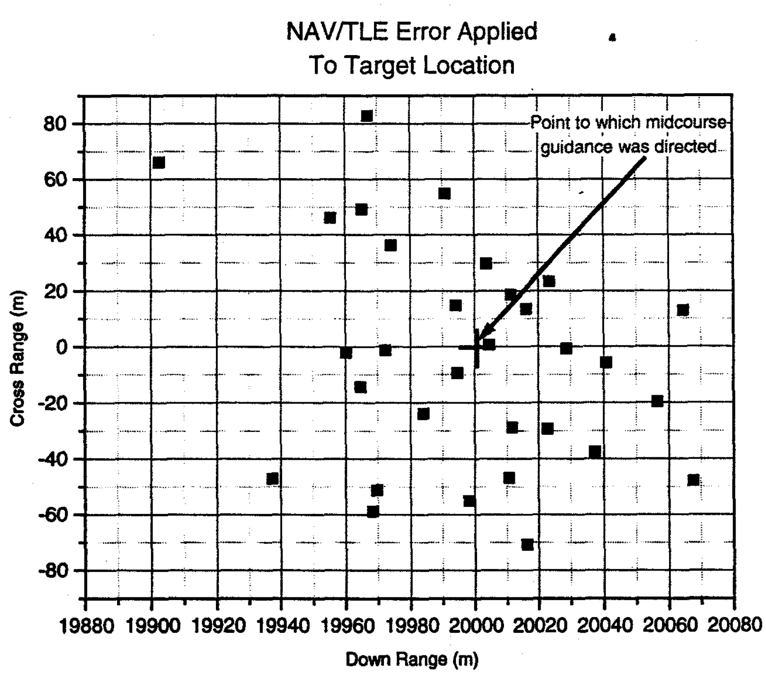


Figure 2b. Jammed target locations seen by seeker
At start of acquisition

Analysis

The results presented here are for both the HVFT and maneuvering target scenarios, using unjammed and jammed environments. The FOV was left unconstrained so that the maximum values encountered for the various scenarios could be determined.

Figures 3 through 6 show the resulting HVFT FOV requirements for 100 and 20 Hz update rates; jammed and unjammed environments. All 31 Monte Carlo runs are plotted for each update rate shown. Plots for other update rates showed similar trends. The maximum FOV grew slightly and the individual curves differed very little, as update rates became smaller. Figure 7 displays the effect of seeker update rate on miss distance. This analysis helped to confirm the expectation that there is little need for high update rates when attacking stationary targets. The FOV requirements for this particular type of target were also bounded. The FOV requirements will help determine the need to gimbal the focal plane. Given restrictions on laser power, number of pixels on target needed for signal processing, pixel resolution, and FOV, the seeker may be able to be fixed and still achieve the necessary angular FOV.

Figures 8 through 11 display similar results for the maneuvering target. The required FOV was found to be only slightly larger in magnitude than that for the HVFT. Again the results for the other update rates showed similar trends although the individual curves could be seen to spread out more at lower update rates. This time, however, there is a definite knee in the curve in Figure 12. The update rate necessary to achieve an acceptable miss distance was determined to be 10-20 Hz. It is important to note that the guidance system used was generic and not specifically tuned for this vehicle. A decrease in overall CEP magnitude would likely occur when a guidance, navigation, and control system designed specifically for the SSB was developed. This would reduce the CEP to levels needed to perform the direct attack scenario against all targets. It is likely, however, that the trends for CEP versus update rate would be the same, and 10-20 Hz would still be needed to achieve a successful hit.

Conclusion

The MSTARS methodology allowed the rapid development of a flash LADAR/SSB simulation to determine preliminary performance requirements. The resulting update rate and FOV requirements for the maneuvering target scenario may be difficult to obtain with current scanning LADAR seekers. This alone shows the need to further investigate flash LADAR technology that may be capable of higher update rates than a scanning LADAR. The FOV requirements were also valuable in determining the number of pixels, pixel resolution, and laser power that will be needed to perform these missions. If the FOV requirements can be met without a gimbal on the focal plane, the seeker cost will be lower. This would make the flash LADAR seeker attractive to advanced, low-cost munition concepts.

This type of analysis is typical of what should be performed before beginning any type of hardware acquisition program. The results helped to confirm the feasibility of the flash LADAR concept and will provide program advocacy information, which can be used to help secure necessary funding.

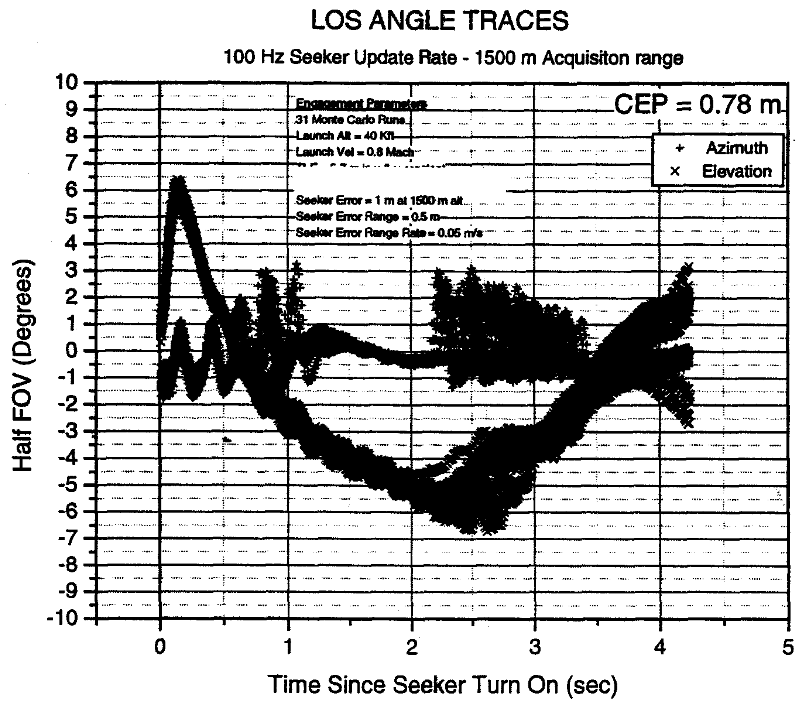


Figure 3. Unjammed azimuth and elevation FOV vs time since seeker turn-on – 100 Hz

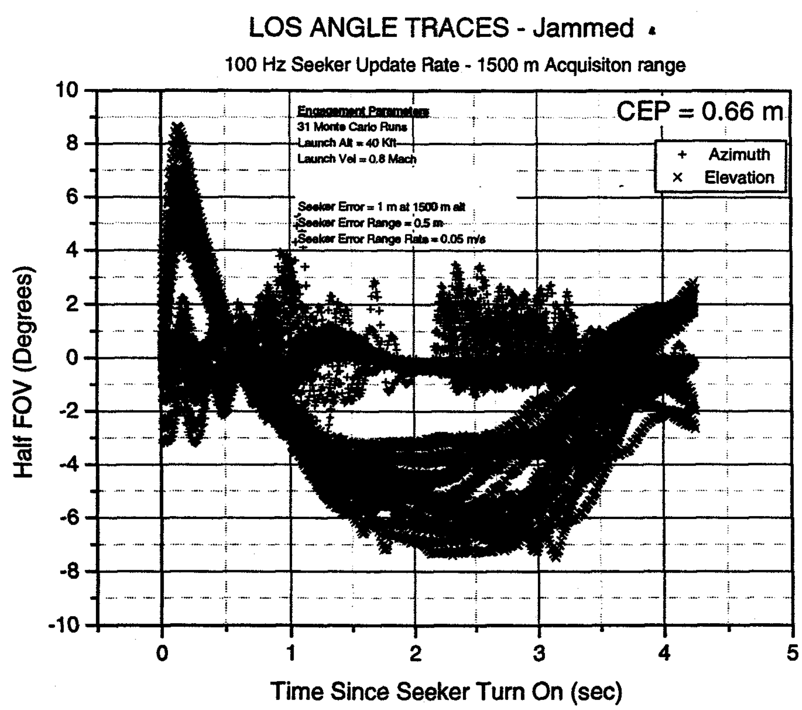


Figure 4. Jammed azimuth and elevation FOV vs time since seeker turn-on – 100 Hz

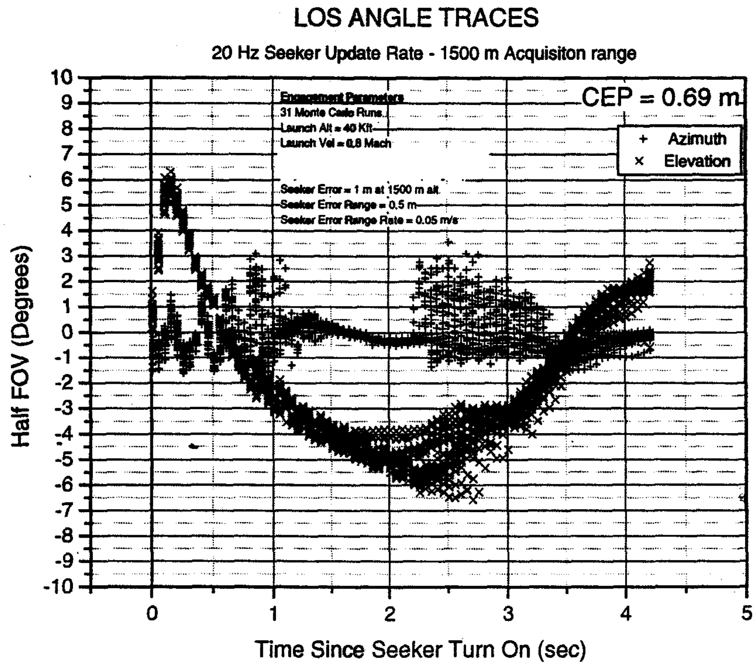


Figure 5. Unjammed azimuth and elevation FOV vs time since seeker turn-on – 20 Hz

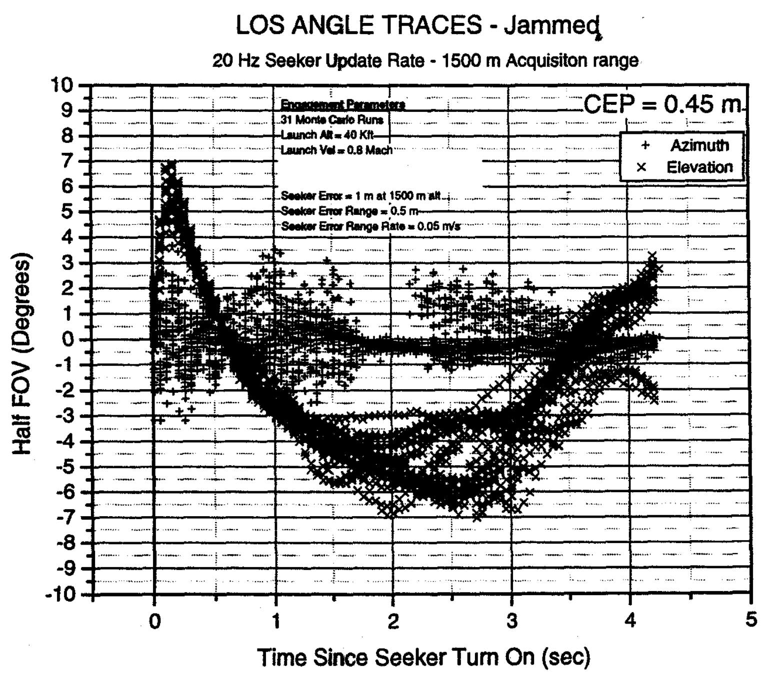
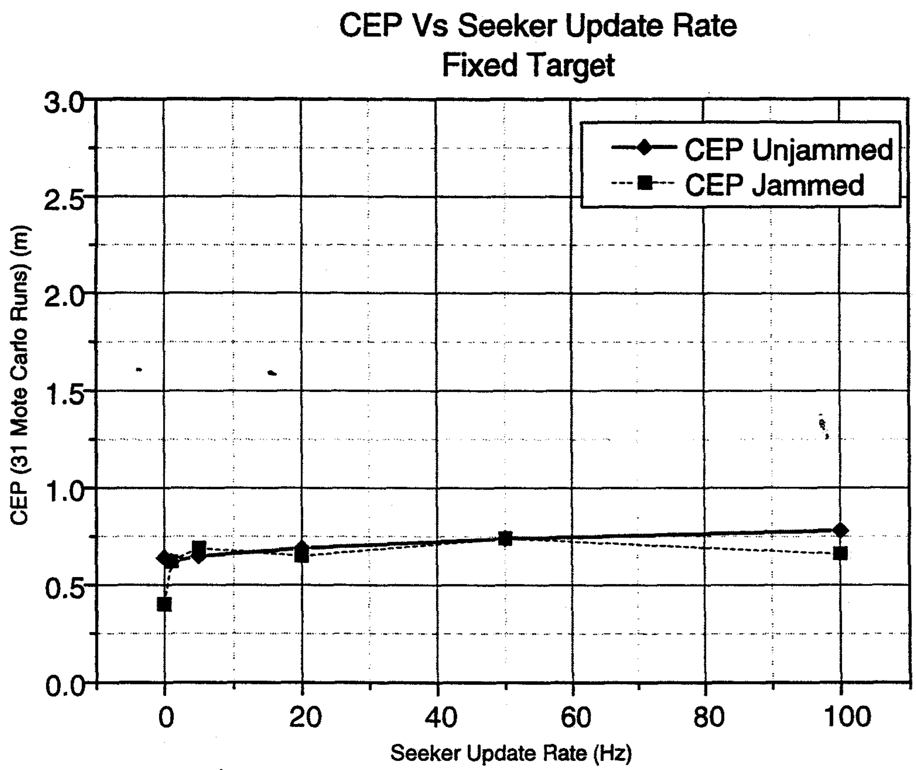


Figure 6. Jammed azimuth and elevation FOV vs time since seeker turn-on – 20 Hz



CEP Summary - Fixed Target

Seeker Update Rate (Hz)	Un-Jammed (m)	Jammed (m)
100	0.78	0.66
50	0.74	0.74
20	0.69	0.65
5	0.65	0.69
1	0.62	0.62
1 Look	0.64	0.40

Figure 7. HVFT CEP versus seeker update rate

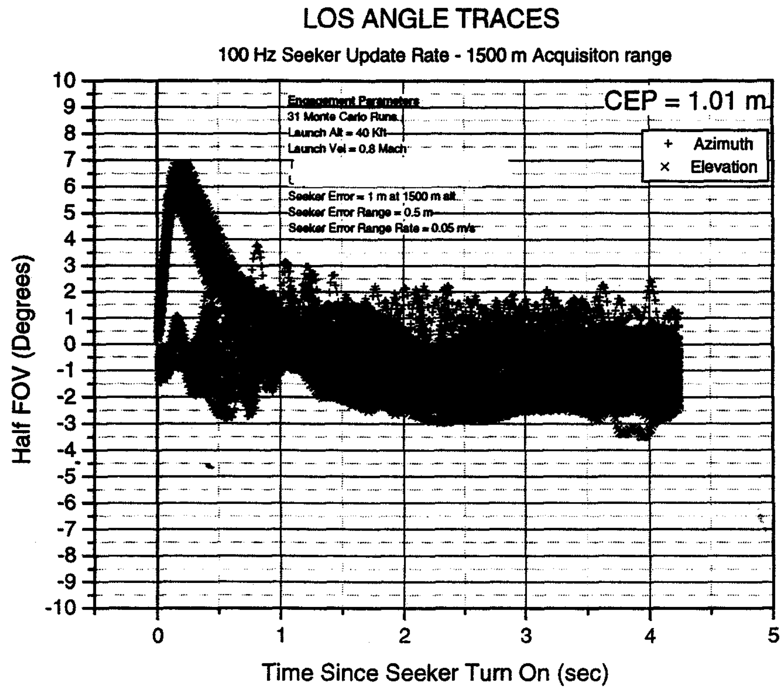


Figure 8. Unjammed azimuth and elevation FOV vs time since seeker turn-on – 100 Hz – maneuvering target

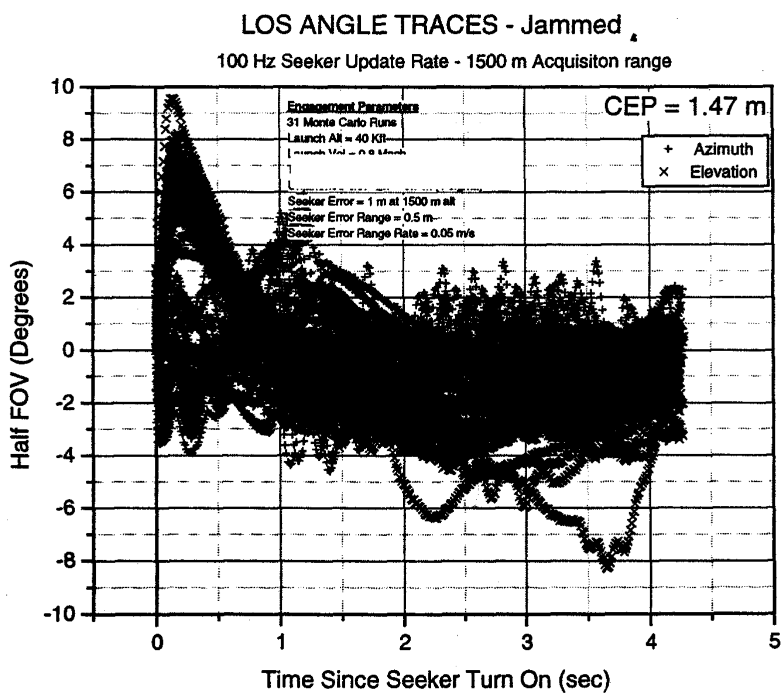


Figure 9. Jammed azimuth and elevation FOV vs time since seeker turn-on – 100 Hz – maneuvering target

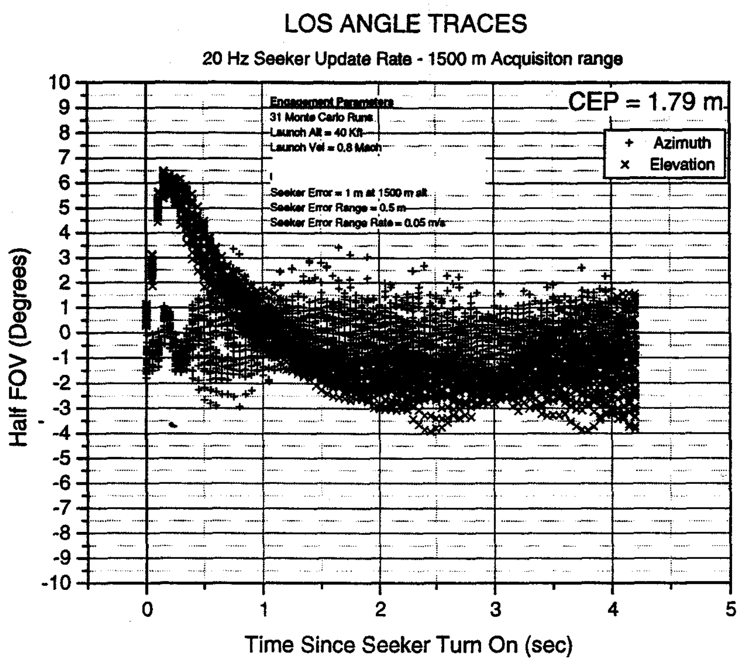


Figure 10. Unjammed azimuth and elevation FOV vs time since seeker turn-on – 20 Hz – maneuvering target

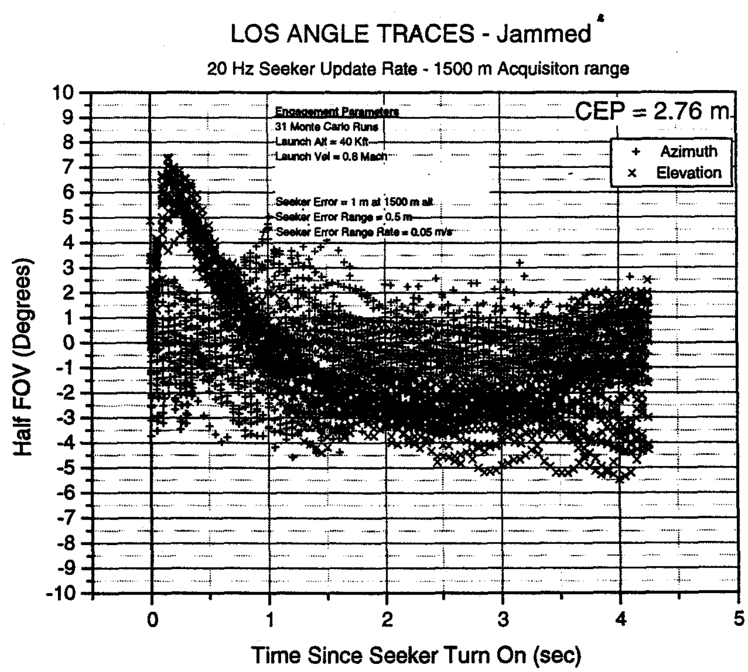
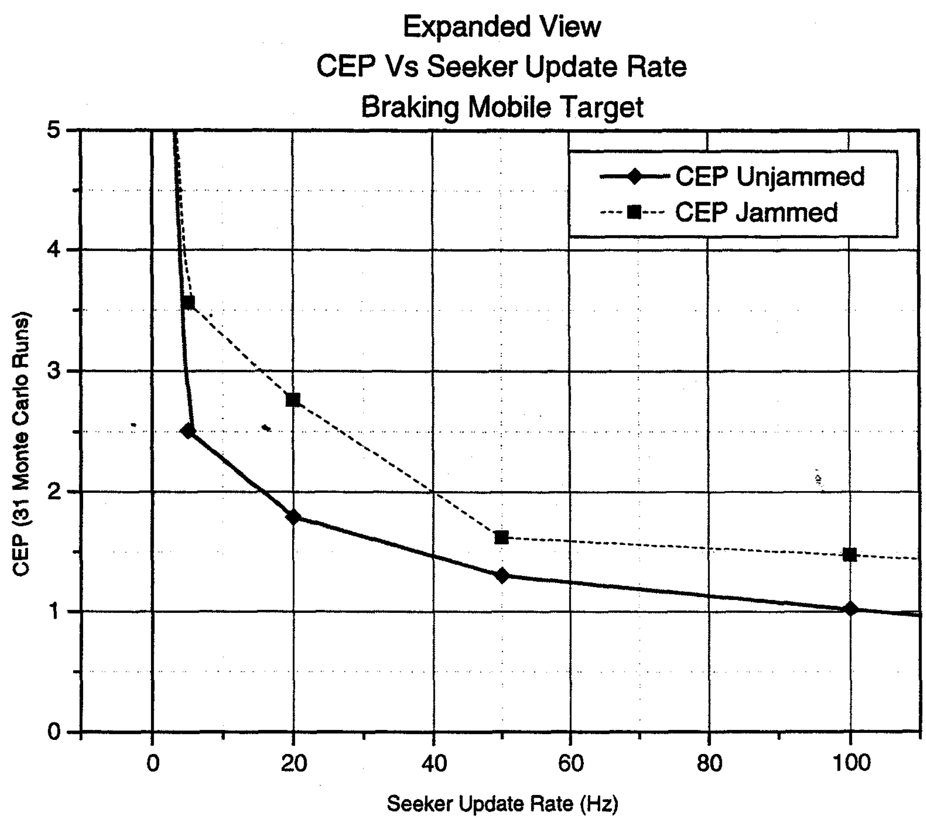


Figure 11. Jammed azimuth and elevation FOV vs time since seeker turn-on – 20 Hz – maneuvering target



<u>**CEP Summary – Maneuvering Target**</u>

Seeker Update Rate (Hz)	Un-Jammed (m)	Jammed (m)
100	1.02	1.47
50	1.30	1.62
20	1.79	2.76
5	2.52	3.56
1	7.76	7.22
1 Look	60.73	58.54

Figure 12. Maneuvering target CEP versus seeker update rate

Using 6-DOF Simulation to Determine Acquisition Requirements for Advanced Staring Focal Plane Array

Craig M. Ewing

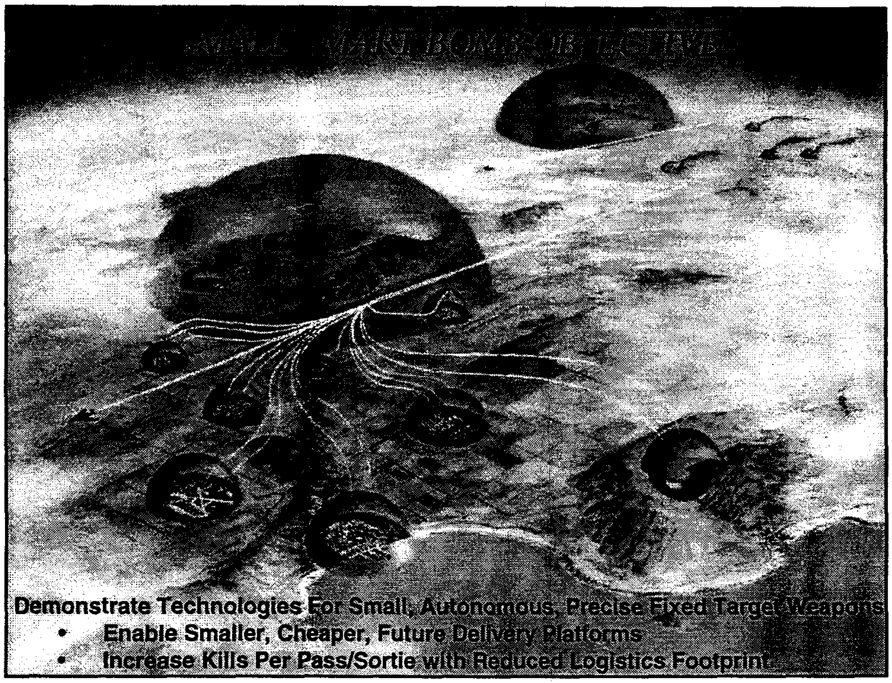
Air Force Research Laboratory/Munitions Directorate
101 West Eglin Blvd., Suite 304
Eglin Air Force Base, FL 32542-6810
ewingc@eglin.af.mil
850-882-8195 ext 3216

Approved For Public Release - 26 May 1999 - Case # 99-169

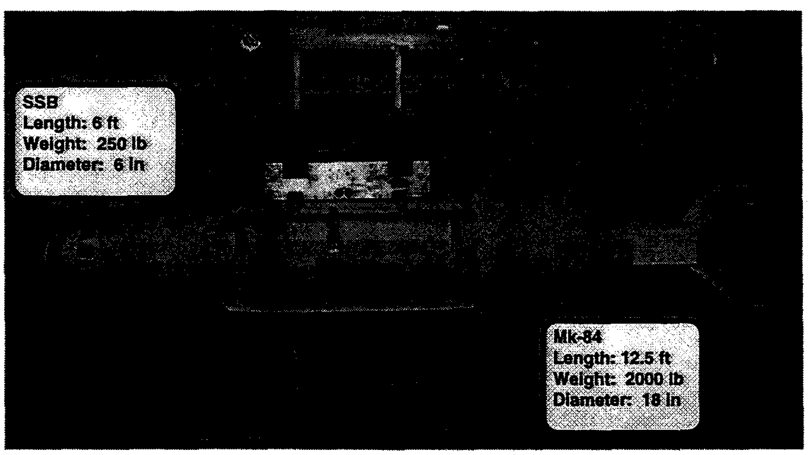
Introduction

- **Need for "smart" munitions to minimize collateral damage and increase number of kills per sortie**
  - **Prompted Air Force to investigate autonomous on-board terminal seekers**
    - **One candidate is staring focal plane LADAR ("flash" LADAR)**
- **Before beginning acquisition program it was desired to understand requirements and performance issues**
  - **In-house 6-DOF simulation and analysis**
    - **Used modular simulation tools and resources (MSTARS) simulation environment**
    - **Visual simulation tool - VisSim**
    - **Munition components developed and maintained in modular architecture**
    - **Allowed rapid development of flash LADAR/munition simulation in only 4 days**

Approved For Public Release - 26 May 1999 - Case # 99-169



SSB Size Comparison



Approved For Public Release - 26 May 1999 - Case # 99-169

SSB Properties

- 250 lb class munition
- Guidance system
  - Terminal flash LADAR Seeker (run at update rates of 1-look to 100 Hz)
    - Measured azimuth, elevation, range, and range-rate
  - Extended Kalmàn Filter
    - 9 state - position, velocity, and acceleration
    - Only used for maneuvering case
  - Guidance Law
    - Maneuvering target: optimal to provide desired impact angle and maximum impact velocity
    - Fixed target: proportional navigation (PRO-NAV)
  - 3-fin control system

Approved For Public Release - 26 May 1999 - Case # 99-169

Why was the analysis done?

- Help the Air Force understand the issues associated with flash LADAR on direct attack munitions
  - Investigate effect of seeker update rate on munition performance
  - Determine preliminary field-of-view (FOV) requirements for direct attack munition
    - Fixed target
    - Mobile target performing deceleration maneuver
      - » Slam on brakes at seeker acquisition
- Used noisy 6-DOF simulation of small smart bomb (SSB) vehicle
  - Noisy Seeker measurements
  - Noisy INS
  - GPS navigation errors
    - Unjammed
    - Jammed since launch (~75 sec)
  - Target Location Error (TLE)

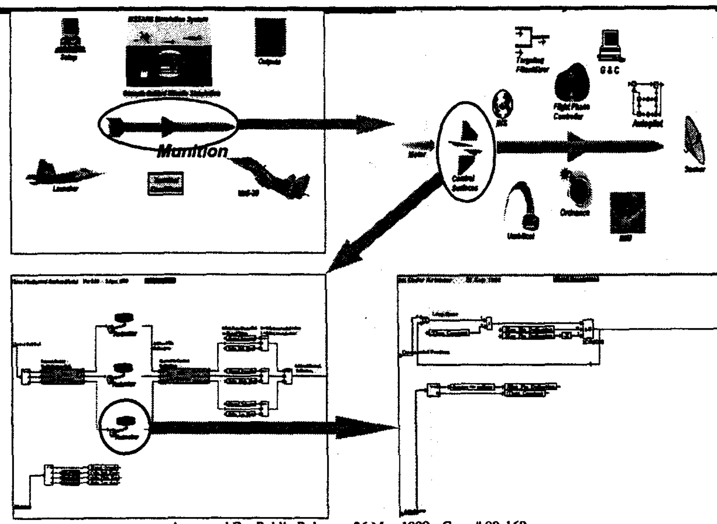
Approved For Public Release - 26 May 1999 - Case # 99-169

Monte Carlo Assumptions

- **Monte Carlo Analysis**
  - **Assumptions**
    - **Acquisition Range:** 1500 meters
    - **Launch altitude :** 40,000 feet
    - **Launch velocity :** Mach 0.8
    - **Desired Imp Angle :** 85 deg
    - **Blind Range:** 200 meters
    - **GPS Nav Error:** Unjammed/Jammed
    - **TLE Error:** Typical
    - **Seeker Errors:**
      - **Range:** 0.5 meters
      - **Range Rate:** 0.05 meters/sec
      - **Angular:** 0.00067 rad = 1.0 meter at 1500 meter acq range
  - **Each set of runs included 1 target downrange position**
    - 20 km
    - No nominal cross range location

Approved For Public Release - 26 May 1999 - Case # 99-169

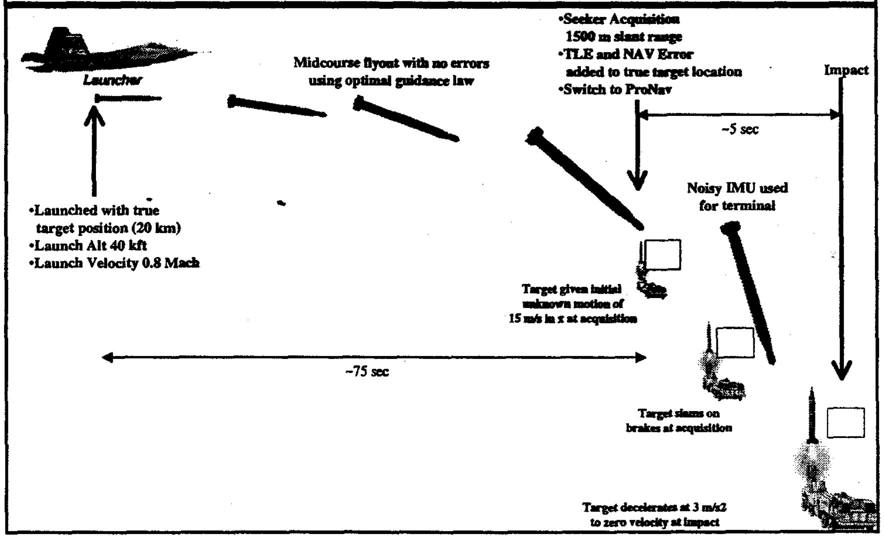
MSTARS - Visual Simulation Development



Approved For Public Release - 26 May 1999 - Case # 99-169

Mobile Target Scenario Flyout

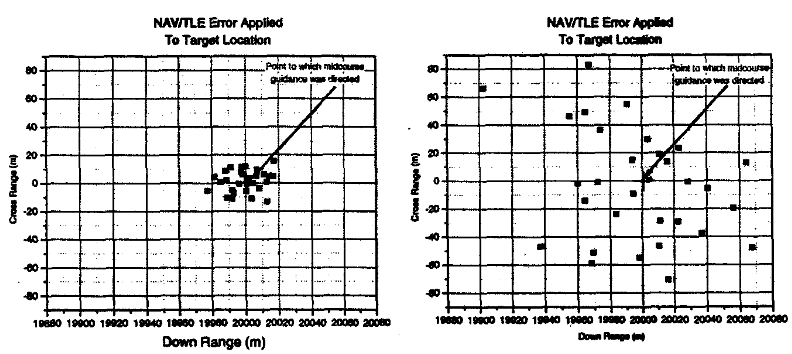
Approved For Public Release - 26 May 1999 - Case # 99-169



Example Target Laydowns

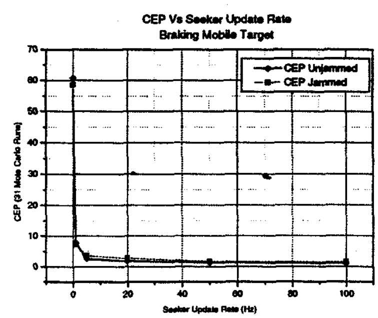
Approved For Public Release - 26 May 1999 - Case # 99-169

Unjammed | **Jammed ~75 sec**

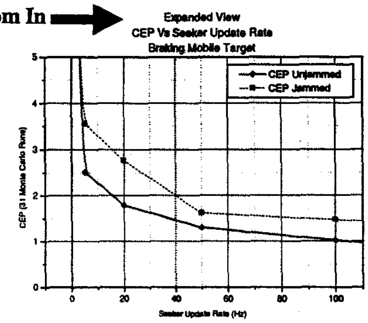


Mobile Target CEP vs Update Rate

Approved For Public Release - 26 May 1999 - Case # 99-169



Zoom In



CEP Summary - Mobile Target

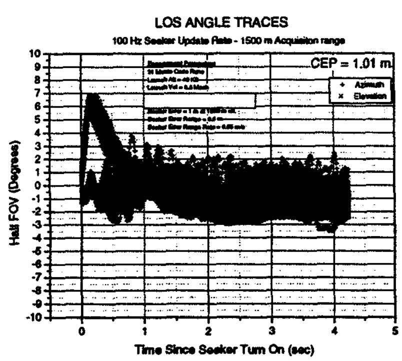
Seeker Update Rate	Un-Jammed	Jammed
100 Hz	1.02	1.47
50	1.30	1.62
20	1.79	2.76
5	2.52	3.56
1	7.76	7.22
1 Look	60.73	58.54

Jammed

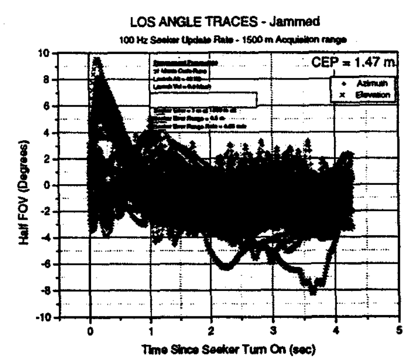
Terminal LOS Angles To Target
Mobile Target - 100 Hz Update Rate
31 Run Monte Carlo

Approved For Public Release - 26 May 1999 - Case # 99-169

Unjammed

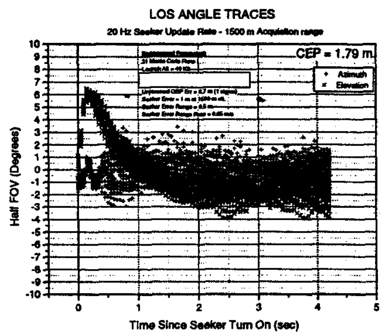


Jammed ~75 sec

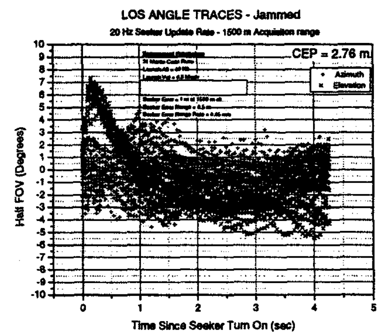


Terminal LOS Angles To Target
Mobile Target - 20 Hz Update Rate
31 Run Monte Carlo

Unjammed

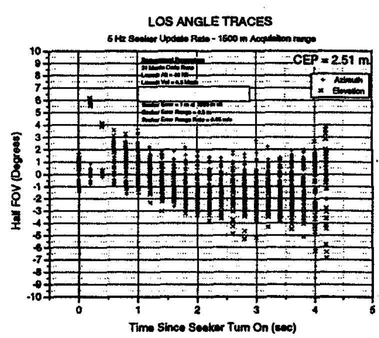


Jammed ~75 sec

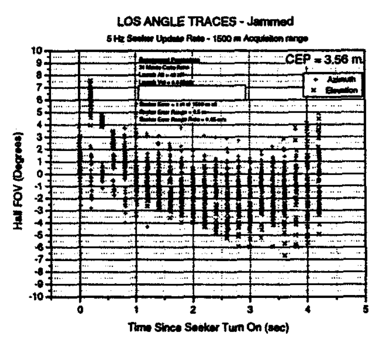


Terminal LOS Angles To Target
Mobile Target - 5 Hz Update Rate
31 Run Monte Carlo

Unjammed

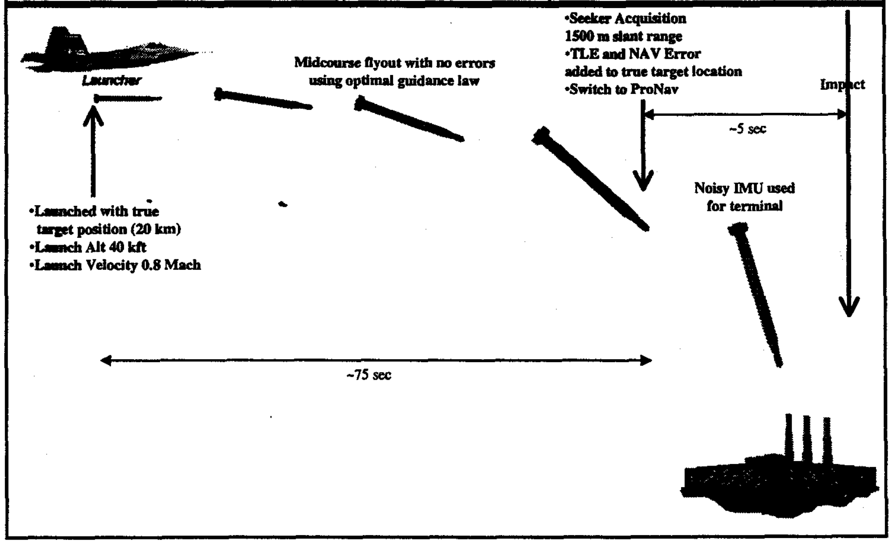


Jammed ~75 sec



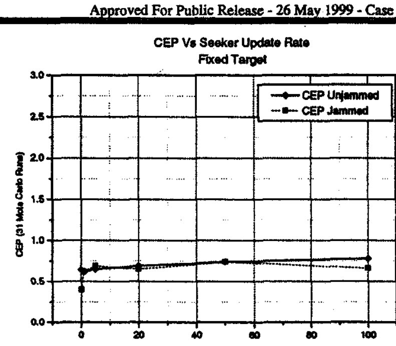
Fixed Target Scenario Flyout

Approved For Public Release - 26 May 1999 - Case # 99-169



Fixed Target CEP vs Update Rate

Approved For Public Release - 26 May 1999 - Case # 99-169



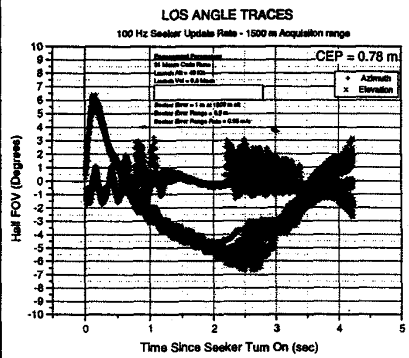
CEP Summary - Fixed Target

Seeker Update Rate	Un-Jammed	Jammed
100 Hz	0.78	0.66
50	0.74	0.74
20	0.69	0.65
5	0.65	0.69
1	0.62	0.62
1 Look	0.64	0.40

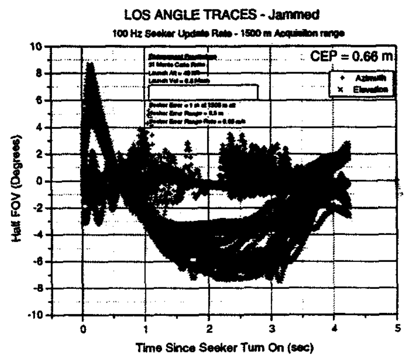
Terminal LOS Angles To Target
Fixed Target - 100 Hz Update Rate
31 Run Monte Carlo

Approved For Public Release - 26 May 1999 - Case # 99-169

Unjammed



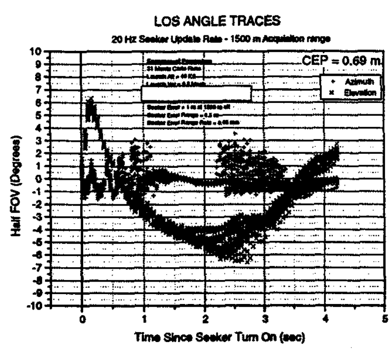
Jammed ~75 sec



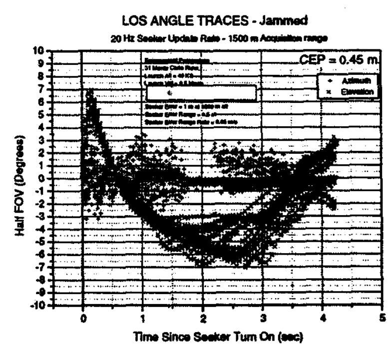
Terminal LOS Angles To Target
Fixed Target - 20 Hz Update Rate
31 Run Monte Carlo

Approved For Public Release - 26 May 1999 - Case # 99-169

Unjammed



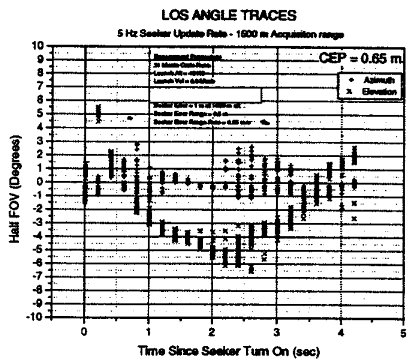
Jammed ~75 sec



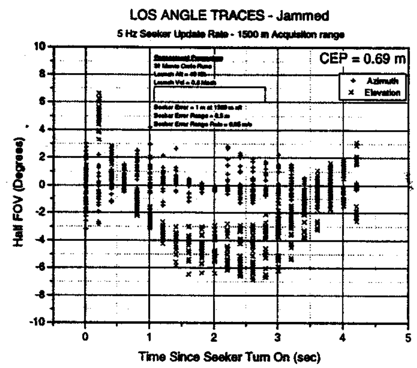
Terminal LOS Angles To Target
Fixed Target - 5 Hz Update Rate
31 Run Monte Carlo

Approved For Public Release - 26 May 1999 - Case # 99-169

Unjammed



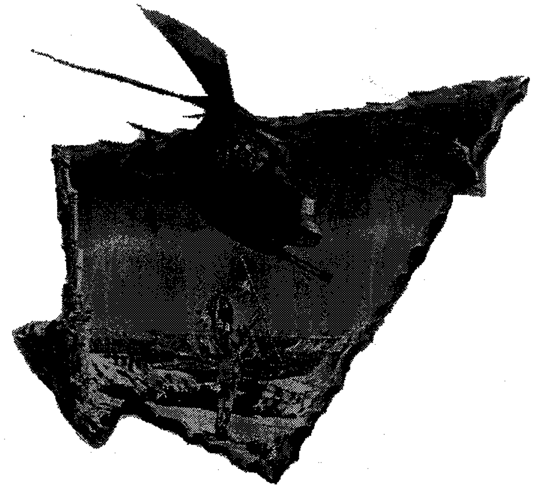
Jammed ~75 sec



Summary

- **Mobile target**
  - **Knee in CEP curve is clearly seen. Updates rates less than 10 Hz are probably not acceptable for direct attack of maneuvering targets.**
- **Fixed target**
  - **Fairly insensitive to update rate**
- **Along with laser power available, pixels required on target, and pixel resolution, the FOV requirement may be small to use a fixed focal plane array**
- **These results were extremely useful in determining the initial feasibility of the flash LADAR for direct attack munitions**

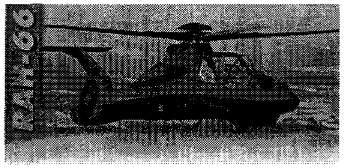
Approved For Public Release - 26 May 1999 - Case # 99-169



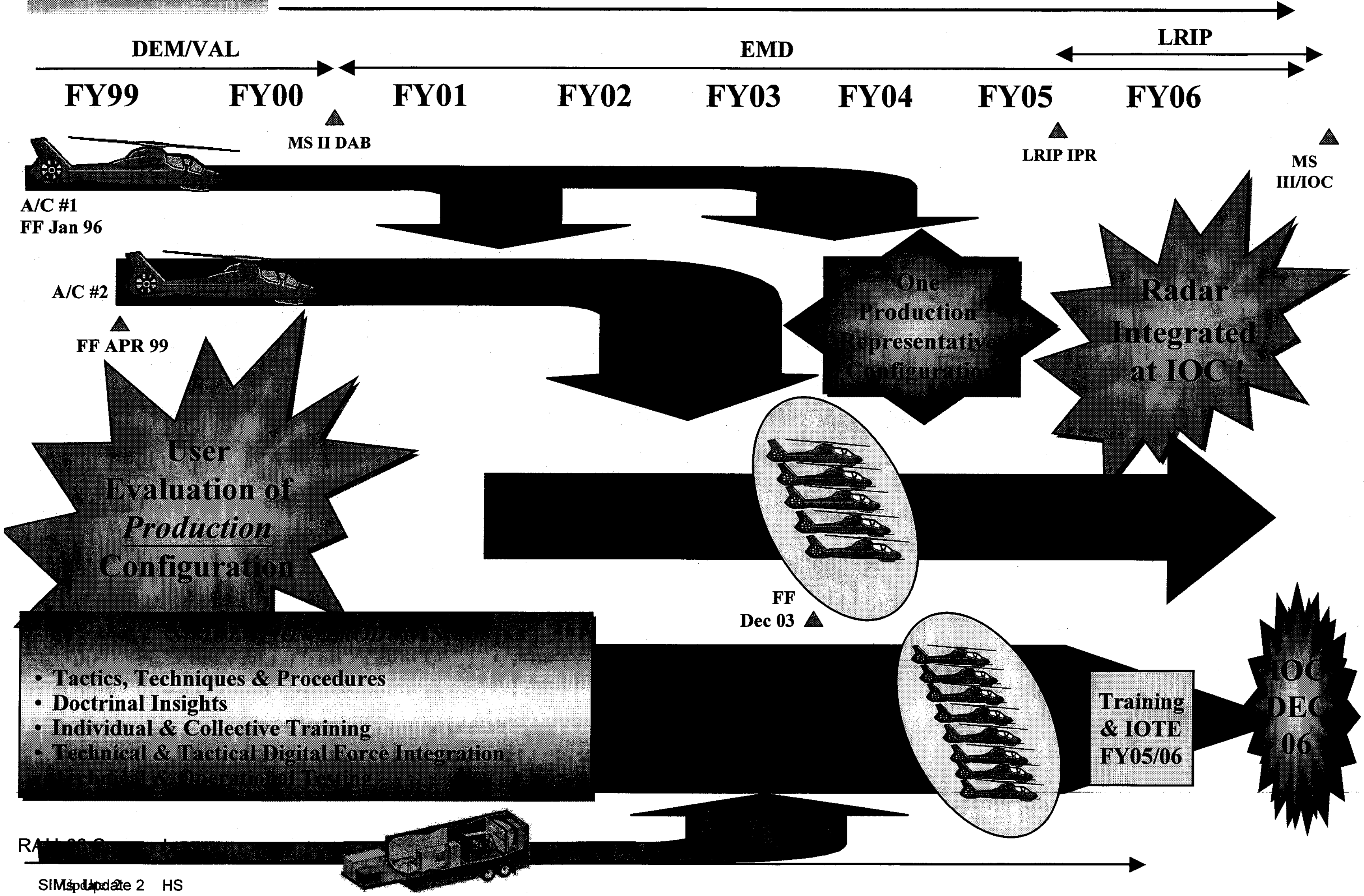
RAH-66 COMANCHE

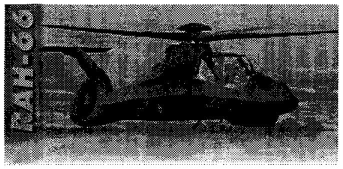
Comanche's Approach to Simulation Based Acquisition

Major Thom Crouch
APM Test & Evaluation
Office of the Program Manager - RAH-66 Comanche
e-mail: croucht@comanche.redstone.army.mil

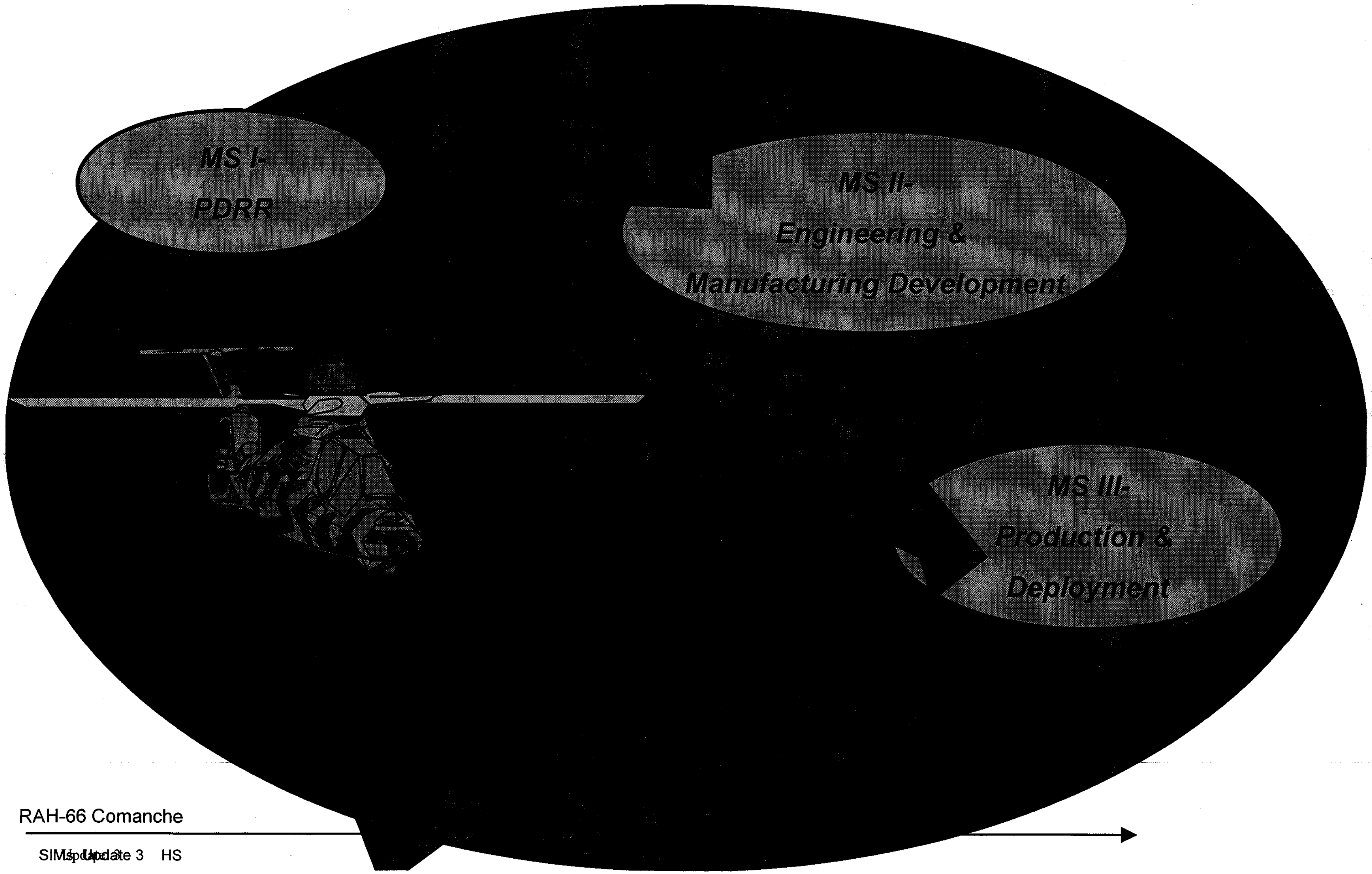


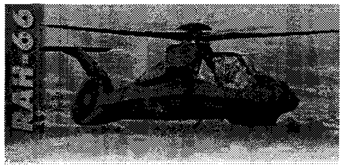
COMANCHE PRE-PRODUCTION PROGRAM





Simulation Support Plan Evolution





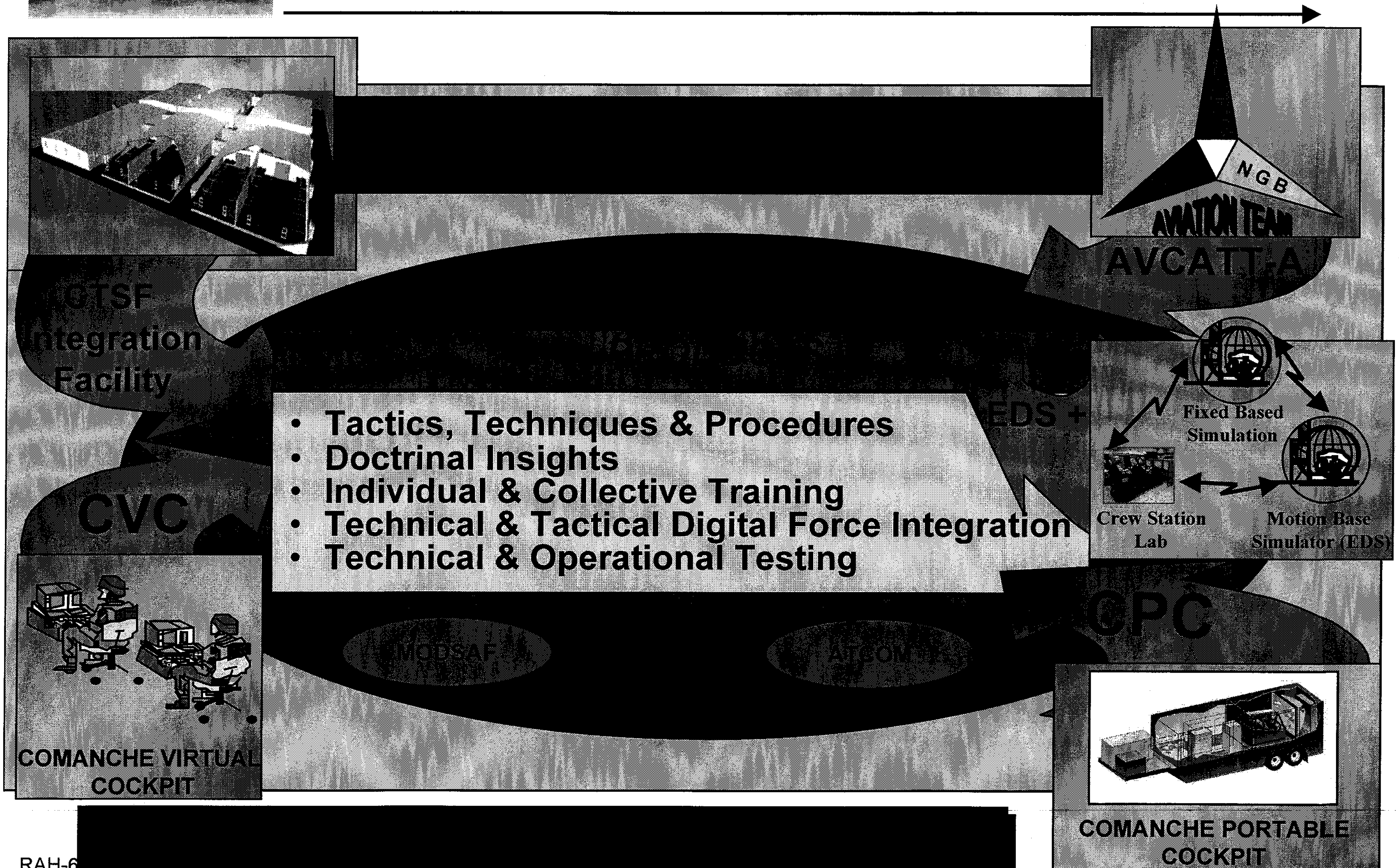
MODELING and SIMULATION REQUIREMENTS

- Engineering Development
- Pilot Vehicle Interface Analysis
- Test and Evaluation
- Tactics, Techniques and Procedures (TTP) Development
- AWE Support
- Individual Training
- Collective Training
- Support Requirements Determination
- Digital Interoperability (System Development)
- Demonstrations

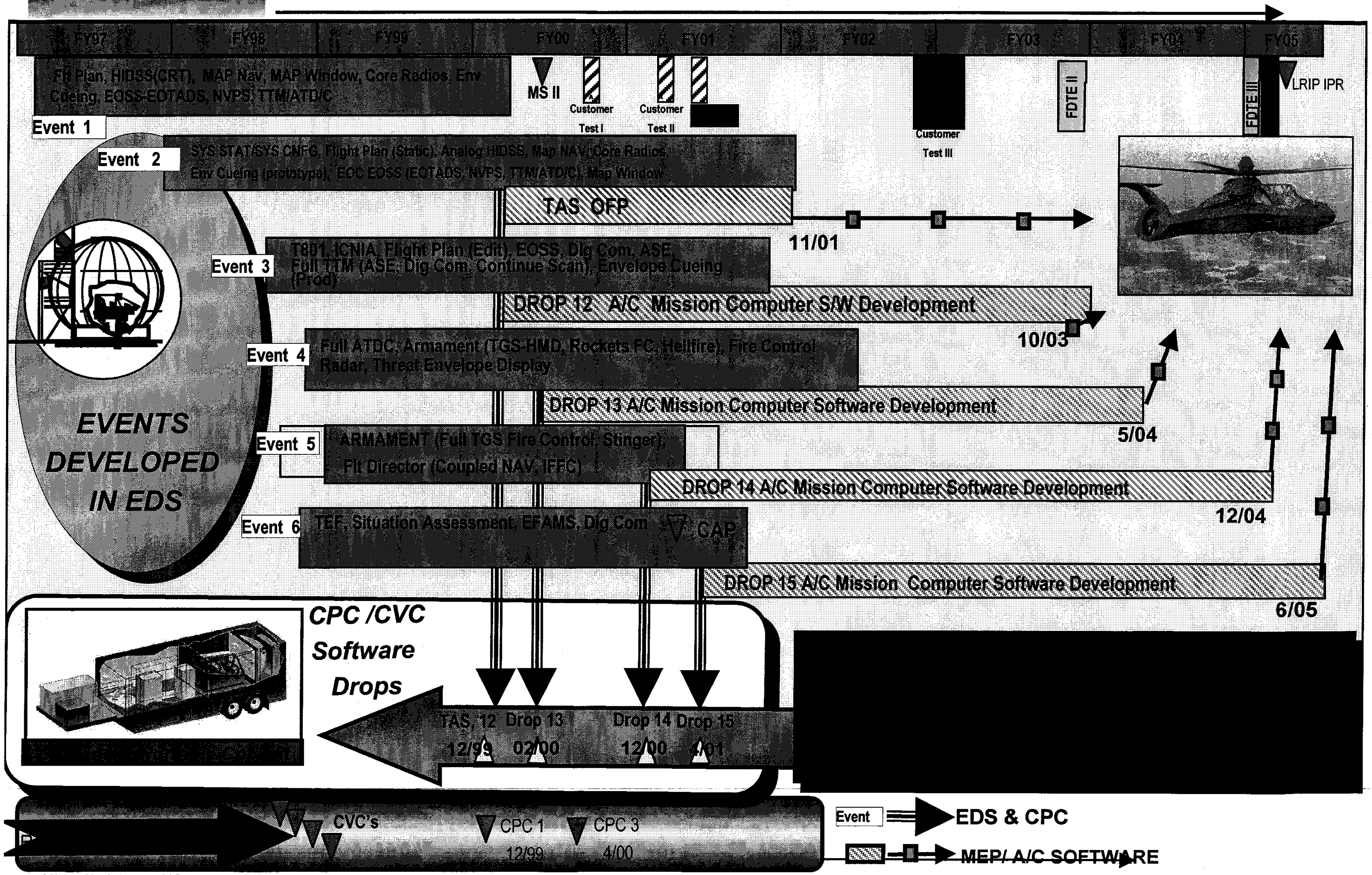
Comanche
RAH-66

And Capability for Data Reduction and Analysis !

SIMULATION TOOLSET

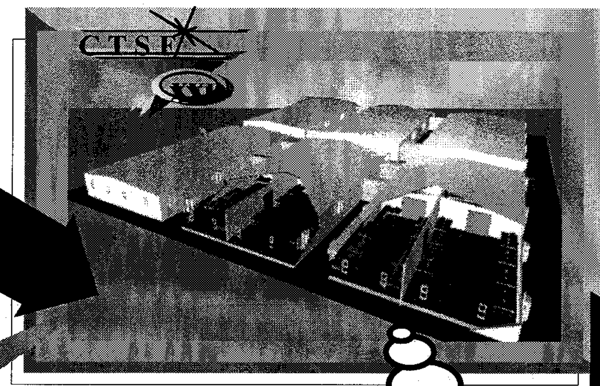


SOFTWARE DROP SCHEDULE As of 25 Jan 99

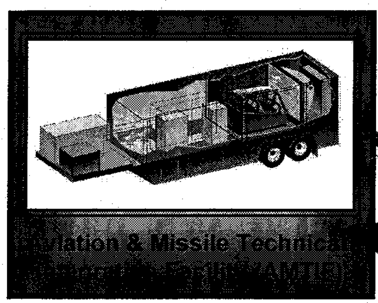


Central Technical Support Facility
Fort Hood, Texas

"Brings Together in one Place"
- Soldiers
- Combat Developer
- Industry
  - Software Programmers
  - Technicians
- Test Community
- Trainers
- Warfighter Systems



Interface to Army Battle Command System



Comanche Focus :

Iteratively -
- Train
- Test
- Exercise
- Evaluate
- Improve & Enhance

Refined and Enhanced Warfighter Tools (Every 3-4 Months)

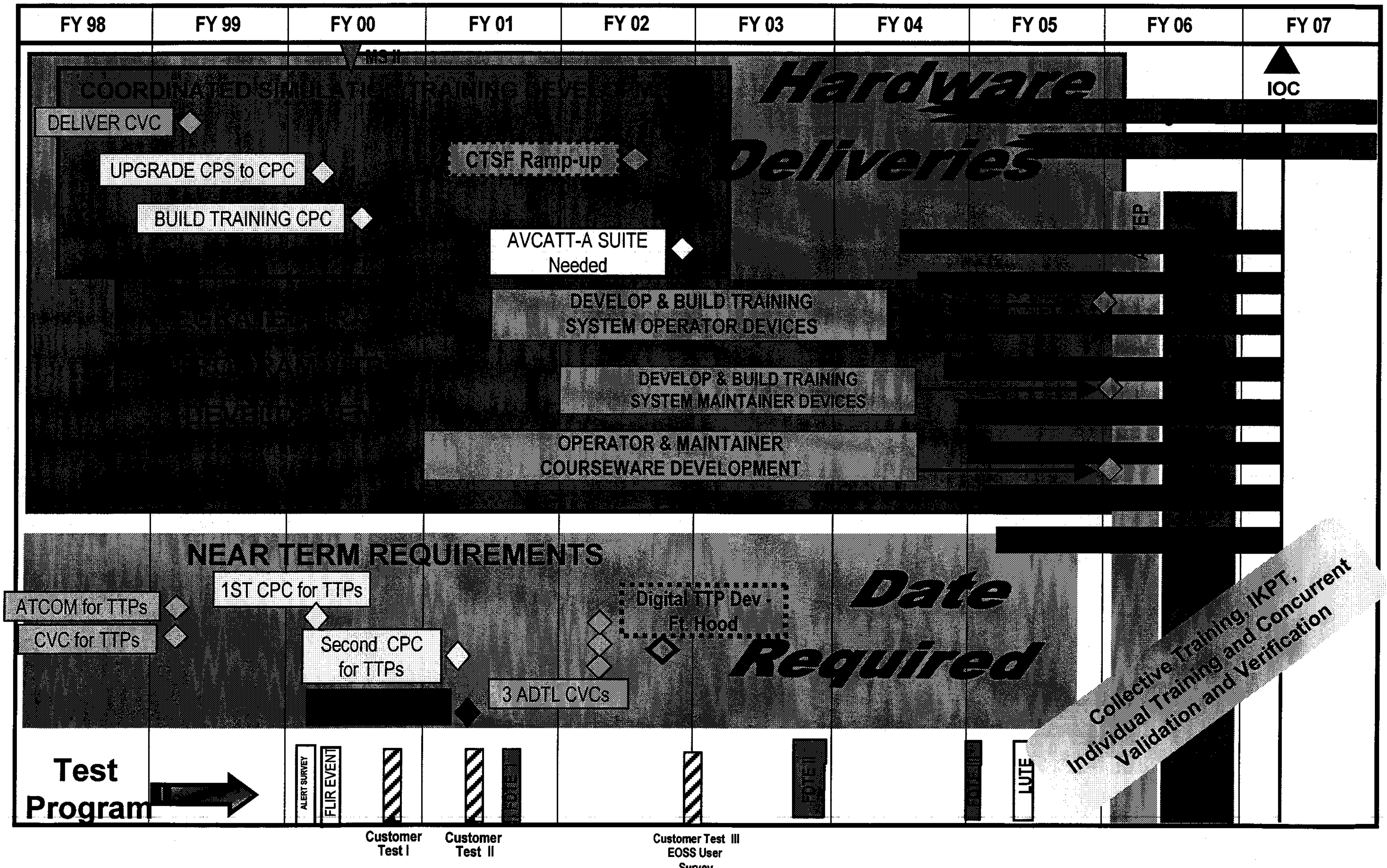
Accelerated Modernization

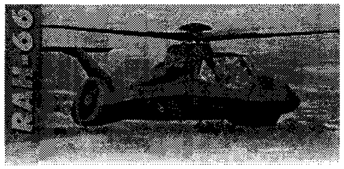
Confirm Digital Interoperability with the Digitized Force

- Hardware - Software - Digital Tactics, Techniques & Procedures

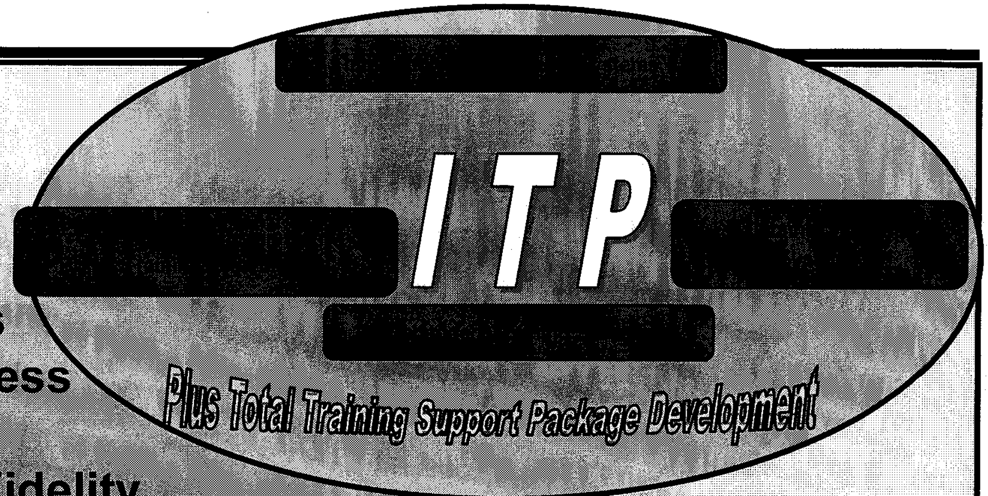
[redacted]

SIMULATION AND TRAINING DEVICE SCHEDULES





INTEGRATED TRAINING PROGRAM (ITP) REQUIREMENTS



- Developed by the Contractor Concurrently With the Aircraft
- Developed IAW TRADOC Systems Approach to Training (SAT) Process
- Base Types, Quantities, Mix and Fidelity of Training Media on Results of SAT Process Analysis
- Include All Hardware, Software, Courseware, Documentation, Consumables and Facilities to Train Active and Reserve Components
- Train 100% of Critical Operator, Maintainer, and Support Tasks
- Tested, Validated, Verified and Ready for Training in the Training Base Prior to Initial Operational Capability

EMBEDDED TRAINING CONCEPTS

User Requirement: Optimize the Use of Embedded Training

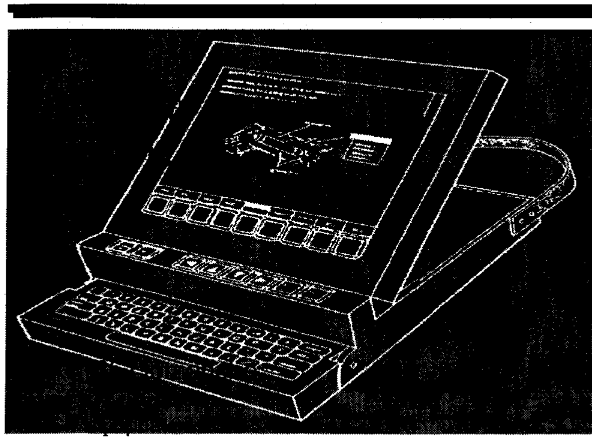
On Aircraft

Operator Embedded Training

- Operational Test, Training & Instrumentation System
- Aviation Survivability Equipment / Electronic Warfare (ASE/EW) Equipment Sensor Stimulation

Off Aircraft

- Portable Maintenance Aid (PMA)
- Aviation Mission Planning Station (AMPS)
  - Full Mission Rehearsal Capability



Portable Maintenance Aid (PMA)

- Primary Media for Maintainer Sustainment Training
- Training Faults Embedded in PMA not Aircraft
- Combines with PMA Instrumentation Pack (PIP) for Full Embedded Maintainer Training Capability

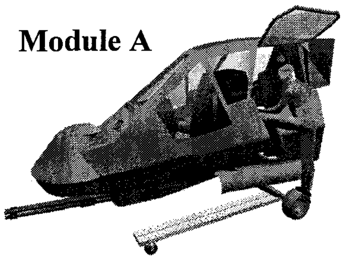
COMANCHE MAINTAINER TRAINING DEVICES

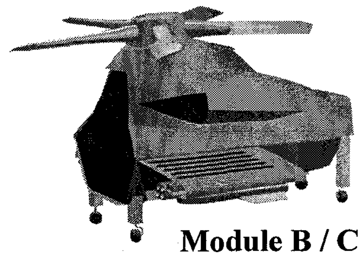
Proposed

Rotor/Transmission/Weapons Bays/ Engine/MEP/SPU/ECU Module

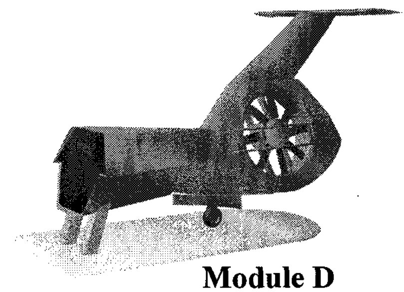
Cockpit/Sensor Turret/ Gun Module

Module A



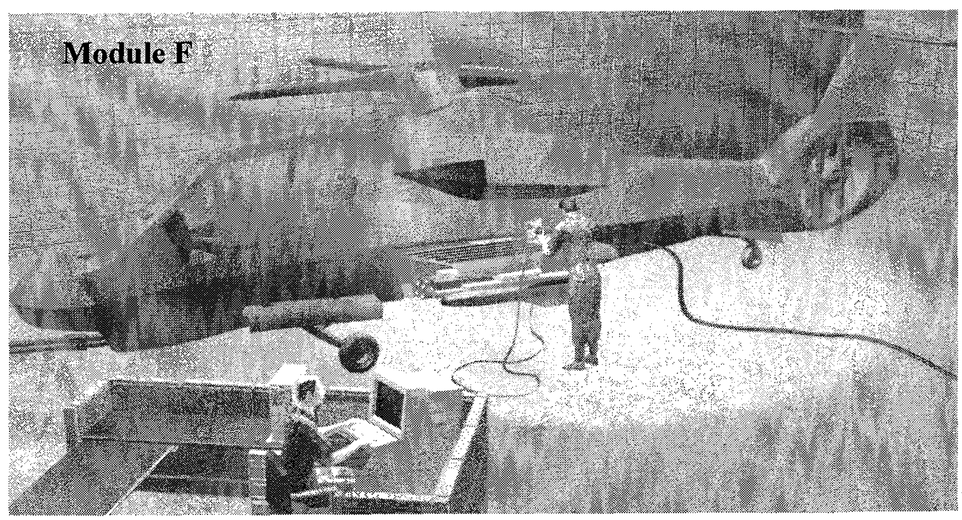


Module B / C

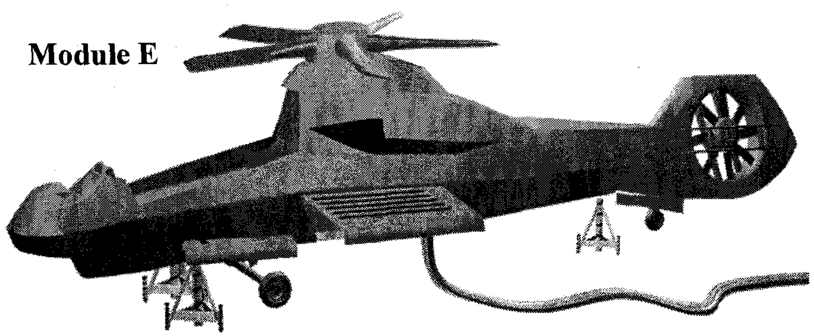


Module D

FANTAIL/ Antenna Module

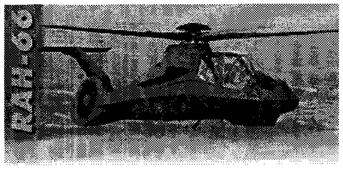


Module E



Landing Gear/Pneudraulic/Fuel Systems Module

Integrated Composite Maintenance Trainer

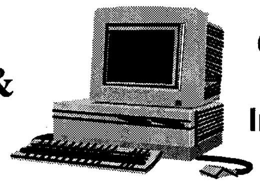


PROPOSED OPERATOR TRAINING DEVICES

Initial Individual Training

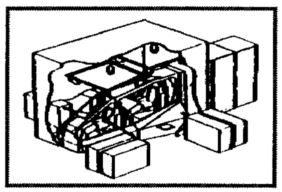
TRAINING BASE

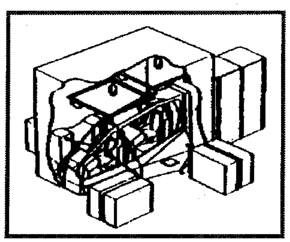
Comanche Virtual Cockpit (CVC) &



Computer Aided Instruction

Cockpit Procedures Trainer (CPT)

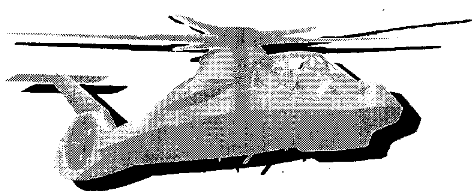




Comanche Mission Simulator
(Hi-Fidelity Cockpit Simulation)

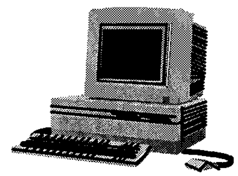
- **Motion / Non-Motion ?**
- **HLA Compliant**

Comanche Aircraft
(Embedded Training)



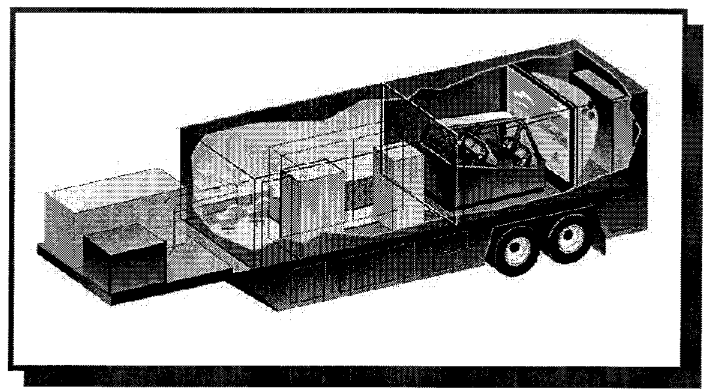
Collective and Sustainment Training

USING INSTALLATION



Computer Aided Instruction & **Comanche Virtual Cockpit (CVC)**

Comanche Mission Simulator
(Mobile Variant)



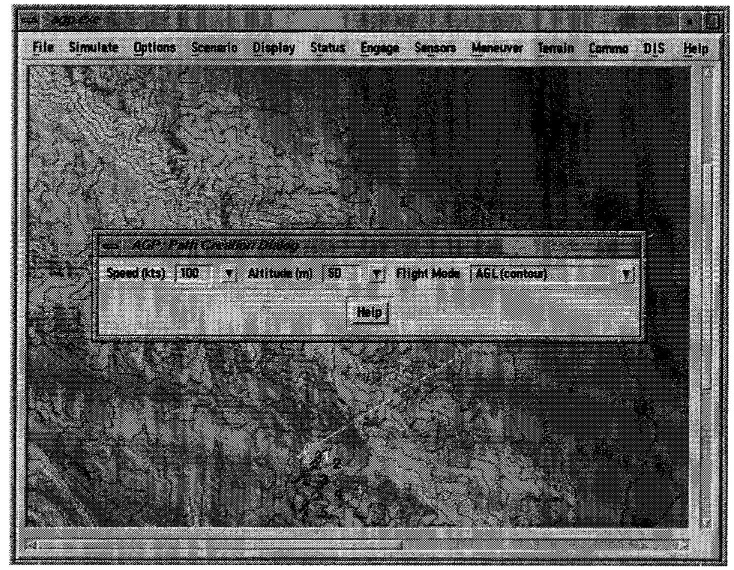
- **Fidelity ?**
- **Transportable**
- **Multiple Cockpits**
- **HLA Compliant**

AVCATT / ARMS

CVC DESKTOP SIMULATOR ELEMENTS

Stealth Viewer for out-the-window view

ATCOM model for the tactical environment

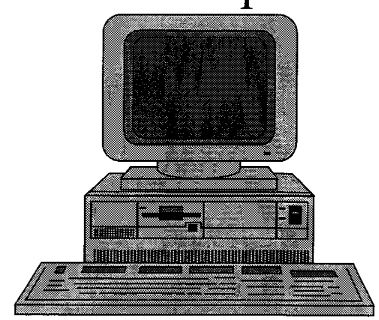


Comanche VAPS for Pilot Interface

FlyBox

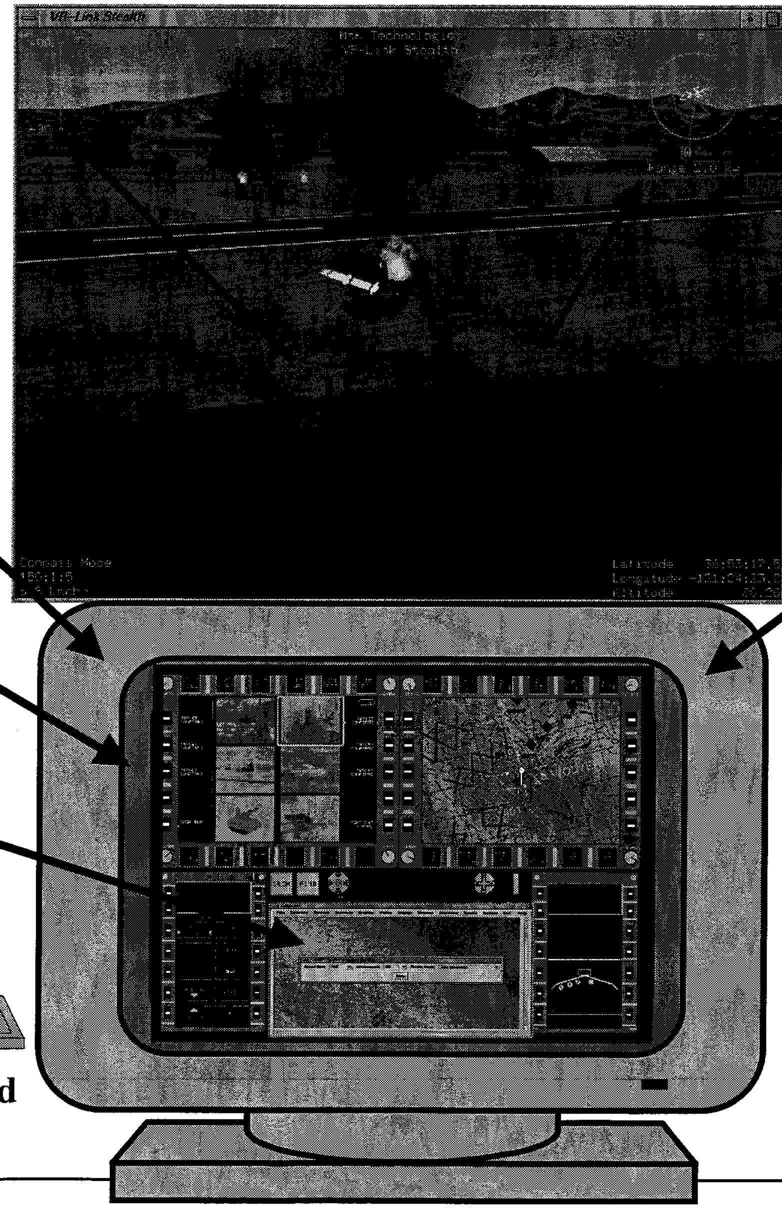
BG Systems
Joystick Control Box

SGI Computer



Two or more processors

POTENTIAL UPGRADES



Sound Enhancements
- Instructions
- Error advisement
- Simulation realism

Flat-Panel Displays

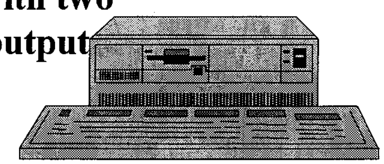
Touch-Screen interaction

IR or TV imagery for EOTADS manual scan/stare

Actual Grips with functional switches

Eliminate the need for ATCOM display

Octane with two graphic output devices

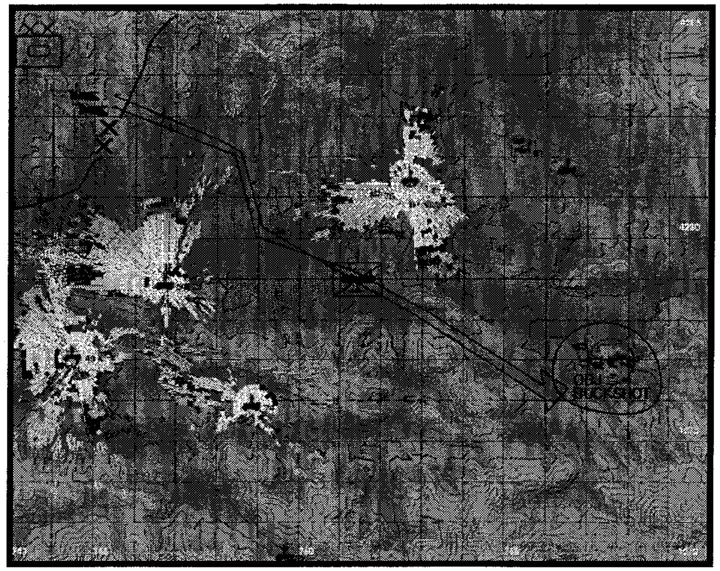


Upgrade as required

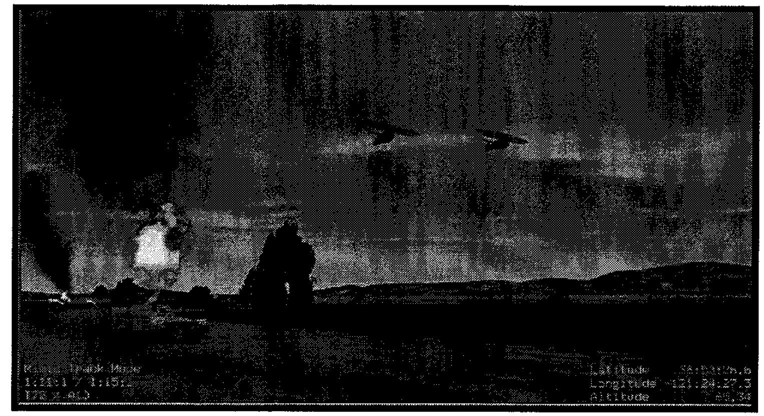
FlyBox

Advanced Tactical COMbat Model

Graphical Display



Stealth Viewer



MaK Technologies VR-Link

Player Interactive Force-on-Force Model
- Stochastic
- Up to Brigade-Level Combat Interactions
- DIS Compliant

High Resolution for Rotorcraft Systems
- Validated Detection Modules
- Validated Radar Clutter & Propagation Modules
- 6-DOF Aerodynamics

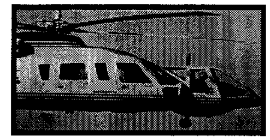
ADDITIONAL RAH-66 MODELS

[redacted]

- Modified S-76 Aircraft
- Demonstrate Fantail Requirements

[redacted]

- Modified S-76 Aircraft
- Flight Control Laws
- MEP
- NVPS



[redacted]

- Transportability
- MANPRINT/Human Factors

[redacted]

- CH-47 & Tower
- TAS

[redacted]

- Planned as Maintenance Trainers after Completing Test Flight

[redacted]

- Full Scale Model
  - Low Observable Tech
  - Radar Reflection
  - Low Observable Material

Propulsion System Test Bed

[redacted]

- Demonstrate 20mm Gun Feed System

COMANCHE IS A SUCCESS STORY

171 Kts Forward
204 Kts TAS (Dive)
75 Kts Left Sideward
65 Kts Right Sideward
70 Kts Rearward Flight

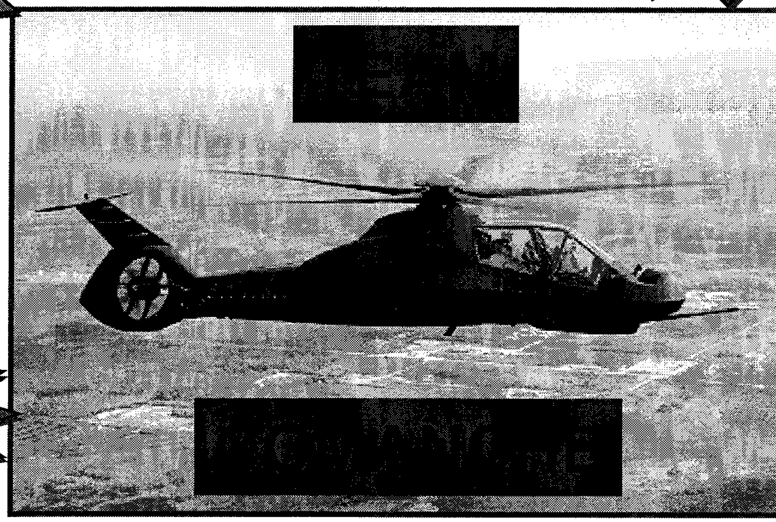
T801
Builds on T800 Success
17% Power Increase

2.0G Pull-Up @ 100 Kts
2.15G Pull-Up @ 120 Kts

PSTB
200 Completed of 200 Hours MQT
669 Hours Total

First Flight
January 4, 1996

112 Flights
124.8 Hours to Date



Demonstrated Integrated Architecture

TSM Representatives in Plant

Radar Signature Model Testing Successful

PMA
In Use

T800
Easily Maintained
Lightweight
High Power
Low Fuel Consumption
Military & Civilian Qualified

Combined Test Team Operational

Dual Mode "Eye Safe" Laser Demonstrated

Digital Flight Control System Minimizes Pilot Workload

Force XXI Activities
Global 97
SIMEX - Sep 97
DIV XXI - Nov 97

SUMMARY

Put the *INTELLECTUAL* before the *PHYSICAL* -

Simulation Based Acquisition

. . . From Concept Exploration Through Operation and Support Provides -

- **Capability Leap Ahead**
  - **Tactics, Techniques & Procedures Development**
  - **Doctrinal Insights**
  - **Technical and Tactical Digital Force Interoperability and Integration**
  - **Individual & Collective Training**
  - **Demonstrate Early Operational Capability Through Simulation**
- **Technical and Operational Testing**
- **Reduced Lifecycle Cost**

INFORMATION SUPERIORITY THROUGH INTELLIGENT INFORMATION OPERATIONS

Dr. John W. Sheppard
ARINC
2551 Riva Road
Annapolis, MD 21401
jsheppar@arinc.com

Abstract

The information revolution has created the ability for creating powerful tools to support the warfighter. Tools for collecting, analyzing, and communicating information are being created to improve the efficiency and efficacy of conducting military operations. Unfortunately, the same information revolution has introduced new vulnerabilities whereby adversaries can acquire, exploit, deny, or destroy information needed to support mission objectives. Information warfare has emerged to provide a new wave of warfare in which the focus has shifted from massive destruction of enemy physical assets to surgical attack on information assets. In this paper, we present a framework for supporting information warfare and information operations using advanced techniques from artificial intelligence and control theory. Specifically, we discuss the combination of techniques from approximate reasoning, dynamic programming, and game theory to define a capability to support the conduct of information operations.

Introduction

Information systems have become an essential element of military, government, commercial, and academic operation. The proliferation of computers, networks, and related technologies has provided the capability to rapidly collect, store, analyze, and disseminate information for a variety of purposes. The expediency, efficiency, productivity, and profitability of organizations and individuals have been significantly enhanced by this information revolution. The military especially benefits from this progress by providing decision makers unprecedented quantity, quality, and timeliness of information. The commander with the ability to know the order of battle, analyze events, and distribute critical information possesses a powerful advantage.

The benefits afforded by the information revolution are balanced by some problems. Information is a potent weapon and a lucrative target. The environment in which information is disseminated and stored provides a means for unauthorized access and manipulation. Nations, groups, and individuals seek to acquire, exploit, and protect information in support of their objectives. This exploitation and protection of information can occur for economic and political reasons as well as for military advantage. Strategies, both offensive and defensive, are being formulated to address actions involving the denial, exploitation, corruption, and destruction of enemy information. These strategies form the core of Information Operations (IO) and Information Warfare (IW).

In this paper, we discuss a framework for supporting a C3/C4 analyst in information operations. To understand where such a capability will benefit the analyst, we review the concept of the command and control decision and execution cycle, also known as the "OODA Loop." The OODA loop consists of four distinct phases corresponding, respectively, to *observe*, *orient*, *decide*, and *act*.

The first phase of the OODA loop is the observation phase. At this point, the analyst or command collects information about the battlespace (i.e., environment) within which information operations will occur. Typically, observation is constrained to data collection from sensors and any processing necessary to support the assessment of the information in the next phase. The second phase is orientation. In this phase, the analyst or commander interprets the information for situation assessment. At this point, inferences are drawn from the information that has been inferred to predict additional attributes about the situation (e.g., risk and strategy). In the third phase, decision, the commander evaluates the results of situation assessment and decides on an appropriate course of action. The resulting orders are passed to those who will execute the orders in the fourth phase, action.

☒ DISTRIBUTION STATEMENT A:
APPROVED FOR PUBLIC RELEASE: DISTRIBUTION 1S UNLIMITED

☐ DISTRIBUTION STATEMENT B:
DISTRIBUTION AUTHORIZED TO U.S. GOVERNMENT AGENCIES ONLY; (Indicate Reason and Date). OTHER REQUESTS FOR THIS DOCUMENT SHALL BE REFERRED TO (Indicate Controlling DoD Office).

☐ DISTRIBUTION STATEMENT C:
DISTRIBUTION AUTHORIZED TO U.S. GOVERNMENT AGENCIES AND THEIR CONTRACTORS; (Indicate Reason and Date). OTHER REQUESTS FOR THIS DOCUMENT SHALL BE REFERRED TO (Indicate Controlling DoD Office).

☐ DISTRIBUTION STATEMENT D:
DISTRIBUTION AUTHORIZED TO DoD AND U.S. DoD CONTRACTORS ONLY; (Indicate Reason and Date). OTHER REQUESTS SHALL BE REFERRED TO (Indicate Controlling DoD Office).

☐ DISTRIBUTION STATEMENT E:
DISTRIBUTION AUTHORIZED TO DoD COMPONENTS ONLY; (Indicate Reason and Date). OTHER REQUESTS SHALL BE REFERRED TO (Indicate Controlling DoD Office).

☐ DISTRIBUTION STATEMENT F:
FURTHER DISSEMINATION ONLY AS DIRECTED BY (Indicate Controlling DoD Office and Date) or HIGHER DoD AUTHORITY.

☐ DISTRIBUTION STATEMENT X:
DISTRIBUTION AUTHORIZED TO U S GOVERNMENT AGENCIES AND PRIVATE INDIVIDUALS OR ENTERPRISES ELIGIBLE TO OBTAIN EXPORT-CONTROLLED TECHNICAL DATA IN ACCORDANCE WITH DoD DIRECTIVE 5230.25. WITHHOLDING OF UNCLASSIFIED TECHNICAL DATA FROM PUBLIC DISCLOSURE. 6 Nov 1984 (indicate date of determination). CONTROLLING DoD OFFICE IS (Indicate Controlling DoD Office).

☐ This document was previously forwarded to DTIC on ____________ (date) and the AD number is __________________

☐ [n accordance with provisions of DoD instructions. the document requested is not supplied because:

☐ It will be published at a later date. (Enter approximate date. if known).

☐ Other. (Give Reason)

DoD Directive 5230.24, "Distribution Statements on Technical Documents," 18 Mar 87, contains seven distribution statements, as described briefly above. Technical Documents must be assigned distribution statements.

JOHN W SHEPPARD
Print or Type Name

5/27/99
Authorized Signature/Date

410-266-2099
Telephone Number

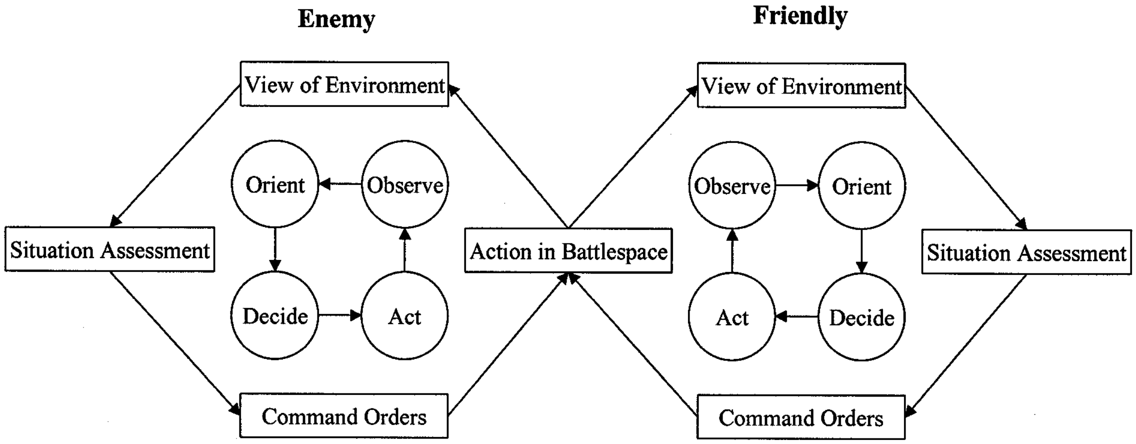


Figure 1. Interacting Decision and Execution Cycles.

Tools supporting the IO process must work within the decision and execution cycle, as shown in the OODA Loop. Specifically, through the intelligence process, data and information are collected about the target system and the processes that use that system. The intelligence process is responsible for collecting information both in support of planning and real-time execution. Therefore, the information to be observed must be stored in a database or made available as collected. Next, tools need to be able to query relevant information related to the current state and infer situation attributes as describe above. Several techniques exist for performing such inference, and we will suggest a particular approach later in this paper. Given the inferred situation, tools must be capable of assessing the available options in the light of the intended goal, the confidence in the current view of the environment, and the expected utility of executing any of the options. Finally, resulting actions must be reflected in the view of the environment, either through prediction of impact or through the collection of additional information (or both).

To ensure accurate representation and analysis of opponent capabilities in supporting the IO decision process, the opponent's corresponding decision process should be included. This can be represented as an interaction of two OODA loops (Figure 1). Since both cycles affect the environment, the friendly decision process should take into account the enemy's decision cycle to predict expected outcome. This results in the interacting decision cycles being represented as a "game," and techniques from game analysis need to be incorporated into the decision aid.

In a game, three major processes take place that coincide with the OOD phases of the OODA Loop (Figure 2). First, data and information are collected from the environment about the target or opponent. This information is used to capture a current "state" of the game and is combined with previously collected data and information to characterize the entire environment. Such characterization may consist of drawing inferences from known information to estimate or predict unknown attributes of the environment. The combination of known and inferred information defines the current "belief state" of the game. The belief state is used, in combination with a specific objective, to select a course of action for achieving the objective. Once the action is taken, the state of the environment changes, and the process repeats.

A Control-Theory View of Information Operations

In general, information operations (and the OODA loop) can be viewed as a special form of feedback (or closed loop) control where desired environment states are obtained by modifying control variables given the current state (Atekson, *et al.*, 1997). Typically, control systems are modeled in one of two ways—through forward models or through inverse models. A forward model uses the current state and the actions that can be applied in that state to predict the results of the actions (i.e., the next state). Typically, this is represented as $s(t+1) = f(s(t),a)$. An inverse model, on the other hand, provides an action given the current state and the desired "outcome," which may be the next state. Thus, the inverse model can be represented as $a = f(s(t),s(t+1))$.

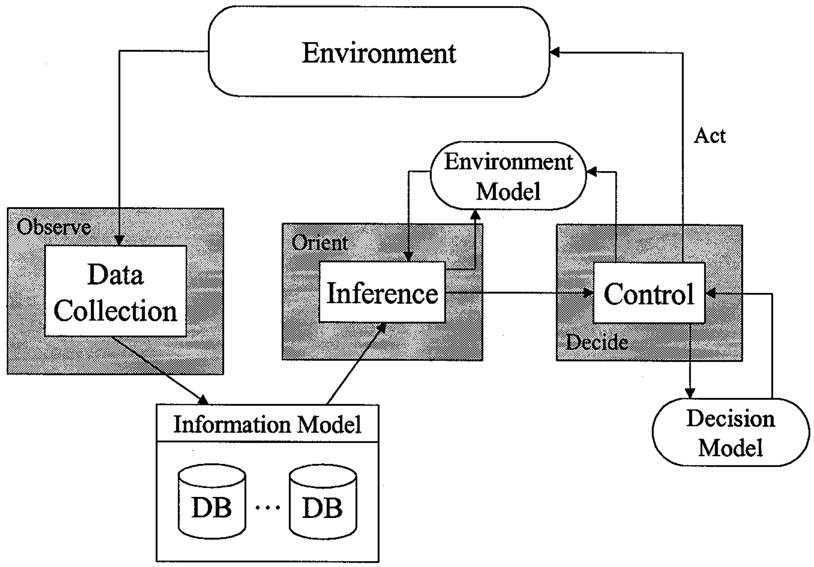


Figure 2. Intelligent IO Process Flow

Alternatively, rather than using the next state as an explicit parameter in the model, an expected payoff, ρ, (e.g., probability of kill) can be used in the models. Then the forward model becomes $\rho = f(s(t),a)$ and the inverse model becomes $a = f(s(t),\rho)$. Using this alternative form, the feedback control problem can be posed as the problem of optimizing the expected payoff for the controller.

The controller contains a "model" of the process being controlled. This may be an explicit model (e.g., a set of differential equations) or an implicit model (e.g., a neural network or lookup table matching states to actions). In the context of intelligent control, it is expected that the controller will process and modify an implicit model since such a model is both computationally efficient and relatively easy to modify based on past experience.

Once the controller determines the proper action to take (based on a control policy that is either stored or computed), the action is translated into appropriate commands or signals for actions to be taken in the environment. In the following sections, we will discuss one possible framework for implementing this architecture.

Markov Decision Processes

The most common form of representation for the types of decision problems outlined above is the *Markov decision process* (Barto, *et al.*, 1995). A Markov decision process (MDP) is defined by a set of states, $\boldsymbol{S}$, a set of actions, $\boldsymbol{A}$, a set of transitions between states, $\boldsymbol{T}$, associated with a particular action, and a set of discrete probability distributions, $\boldsymbol{P}$, over the set $\boldsymbol{S}$. Similarly, $\boldsymbol{T} : \boldsymbol{S} \times \boldsymbol{A} \rightarrow \boldsymbol{P}$. Associated with each action while in a given state is a cost (or reward), $c(s,a)$. Given an MDP, the goal is to determine a policy, $\pi(s)$, (i.e., a set of actions to be applied from a given state) to minimize total expected discounted cost.

Let $f^{\pi}(s_i)$ represent the total expected discounted infinite horizon cost under policy π from state s_i. Let γ ($0 \leq \gamma \leq 1$) be a discount factor, having the effect of controlling the influence of future cost on π. Then,

$$f^{\pi}(s_i) = E_{\pi}\left[\sum_{t=0}^{\infty} \gamma^t c(s_t, \pi(s_t)) \mid s_0 = s_i\right]$$

where $E_\pi[\bullet]$ is the expectation given policy π. We can estimate $f^\pi(s_i)$ for some $\pi(s_i) = a$ as follows:

$$f^\pi(s_i) \approx Q^f(s_i a) = c(s_i, a) + \gamma \sum_{s_j \in \mathbf{S}} p(s_j \mid s_i, a) f(s_j)$$

From this, we are able to establish policy, π, based on the current estimate Q^f; namely, select $\pi(s_i) = a$ such that,

$$Q^{f_i}(s_i, \pi(s_i)) = \min_{a \in \mathbf{A}} Q^f(s_i, a).$$

This equation is in the form of the *Bellman optimality equation* which can be solved for $f(s_j)$ using several techniques such as dynamic programming (Bellman, 1957).

With the combined OODA loop as depicted in Figure 1, we can generalize the development of a policy within the context of *Markov games* (Sheppard, 1997; Sheppard, 1998). A Markov game is an extension of the MDP in which decisions by multiple players must be considered, and these decisions generally conflict. Under the restriction of two-person games, we define $\boldsymbol{S}$ to be a set of states, $\boldsymbol{A}_1$ and $\boldsymbol{A}_2$ to be sets of actions for players 1 and 2 respectively, and $\boldsymbol{T}$ to be a set of transitions similar to the MDP, such that $\boldsymbol{T} : \boldsymbol{S} \times \boldsymbol{A}_1 \times \boldsymbol{A}_2 \to \boldsymbol{P}$. Associated with each player is a cost (or reward) function, $c_1(s,a_1,a_2)$ and $c_2(s,a_1,a_2)$.

In the context of IO, the objective is to find a policy $\pi_1(s)$ that maximizes total expected discounted reward in the presence of an opposing policy $\pi_2(s)$. Value functions for each player analogous to the MDP case can be determined. For alternating games (which is unlikely), policies can be determined for each player given their value functions using minimax. In the event simultaneous games are being played, mixed strategies may be required. For zero-sum games, policies at individual states can be determined using linear programming (Sheppard, 1997). For non-zero-sum games (which would result when the value functions for the two players are not complementary), a linear complementarity problem can be constructed and solved using various numeric techniques such as the Lemke-Howson algorithm (von Stengel, 1998).

Implicit Models of MDPs and Markov Games

Given the large state space of the IO scenario, it is likely that a traditional approach using dynamic programming to solve these MDPs will be infeasible. As a result, some form of function approximation will be required for generalizing from representative state-action pairs to the full range of state-action possibilities. One of the more common approaches to function approximation is the use of feed-forward neural networks.

The traditional feed-forward neural network calculates the output of a given node, O_j as $O_j = \sum_{i=1}^{n} w_{ji} x_i$, where n is the number of inputs to the current node. Learning consists of modifying the weights, w_{ji} in such a way to reduce the network error (calculated as $E = \frac{1}{2}(z - O)^2$, where z is the expected network output and O is the actual network output). This weight update (called backpropagation) is accomplished by determining the gradient of the error surface and modifying the weights in the direction of the gradient. Specifically, the weight update rule for backpropagation can be represented as $\Delta w_{ji} = \alpha(z - O)\nabla_w O$ (Rumelhart *et al.*, 1986).

The standard backpropagation algorithm, while performing well on classification tasks, has been shown to have difficulties solving highly dynamic problems such as control problems. In response to these difficulties, work in reinforcement learning and neural networks resulted in the development of a class of algorithms capable of solving specific types of control problems. In particular, *temporal difference* algorithms have been shown to solve highly complex control problems that are posed as MDPs.

Rich Sutton developed an algorithm for training feed-forward neural networks to solve control tasks that can be modeled as an MDP (Sutton, 1988). Sutton's temporal difference method focuses on the problem of predicting expected discounted payoff from a given state. This method is applied in "multi-step prediction problems" where

payoff is not awarded until several steps after a prediction for payoff is made. At each step, the controller predicts what its future payoff will be, based on several available actions, and chooses its action based on that prediction. However, the ramifications for taking the sequence of actions are not revealed until (typically) the end of the process.

According to Sutton, the temporal difference method is an extension of the prototypical supervised learning rule that is based on gradient descent (as described above). If we assume a prediction depends upon a vector of modifiable weights w, and a vector of state variables s, then supervised learning uses a set of paired state vectors and actual outcomes to modify the weights to reduce the error between the predictions and the known outcomes.

The standard, supervised learning method works best for single-step prediction problems. For multi-step prediction, the vector w cannot be updated until the end of the sequence, and all observations and predictions must be remembered until the end of the sequence. Sutton's temporal difference method permits incremental update and is based on the observation that

$$z - P_t = \sum_{k=t}^{m} (P_{k+1} - P_k)$$

where P_t is the predicted payoff at time t, m is the number of steps in the sequence, and $P_{m+1} = z$. In this case, the supervised learning rule becomes

$$\Delta w_{ji}^t = \alpha(P_{t+1} - P_t)\sum_{k=1}^{t} \nabla_w P_k \,.$$

This update can be computed incrementally because it depends only on a pair of successive predictions (P_t and P_{t+1}) and on the sum of past values for $\nabla_w P_t$.

Sutton goes on to describe a family of temporal difference methods based on the influence past updates have on the current update of the weight vector. These methods are based on a parameter, $\lambda \in [0,1]$, which specifies a discount factor in the prediction equation. Sutton refers to this family of equations as the TD(λ) family. When $\lambda = 0$, past updates have no influence on the current update. When $\lambda = 1$, all past predictions receive equal weight. Assuming it is desirable for the update procedure to be more sensitive to recent predictions than to distant predictions, the changes are weighted according to λ^k. Thus the update equation becomes

$$\Delta w_{ji}^t = \alpha(P_{t+1} - P_t)\sum_{k=1}^{t} \lambda^{t-k} \nabla_w P_k \,.$$

Note this equation (and the original gradient descent equation) assumes a single linear combination of weights. This means that for a function to be learned, that function must itself be linear in the inputs (i.e., underlying concepts must be linearly separable). This limitation can be addressed by using the generalized delta rule as described in (Rumelhart *et al.*, 1986).

Modeling Belief States with Bayesian Networks

Given a neural network for computing a value function, we need a method of representing the state of the control problem being solved. For the IO problem, we suggest using a Bayesian network to capture the current belief in the state of the network under attack. A Bayesian network is a network where the nodes correspond to random variables and directed edges correspond to dependence (i.e., causal) relationships between the random variables (Pearl, 1988).

Within the context of IO, a node in the network will correspond to some attribute of the environment. Expected values for these attributes are derived from known attributes of the environment (obtained through intelligence sources) and conditional probabilities of other values given certain known values within the environment. Using

basic operations from probability theory, given a Bayesian network and certain known data, probabilities can be propagated through the network to derive expectations for unknown attributes of the network.

Bayesian networks are constructed such that the "roots" of the network (defined to be those nodes that are conditioned on no other random variables) have "prior" probabilities associated with them. Interior nodes of the network have conditional probability tables associated with them indicating the probability of the variable taking on some value given a value of the ancestor nodes. In addition, the networks are constructed to be "acyclic" (i.e., no path exists through the network from a node back to the same node).

Combining Bayesian Networks and Markov Decision Processes

Key to determining a policy that solves a particular MDP is the proper representation of the state of the process. The IO scenario assumes the decision process corresponds to controlling the state of the environment until it reaches some desired state maximizing a particular objective function. Using this approach, we see that the Bayesian network captures the state of the environment. From the beginning of the attack scenario, we establish a "baseline" state using intelligence data, likely environmental conditions, and likely mission scenarios. Key attributes will be derived from the Bayesian network to form the actual state description for the Markov decision process. Note that this state need not represent the state of the entire environment. Such a state representation would be too massive to be able to process efficiently. Rather, the state representation will focus on the area of the environment of interest to the commander.

From the Bayesian network, an estimate of the current state will be formulated. Based on that state and a set of objectives to be achieved, feasible actions will be considered. The action selected will be one to maximize the ability to achieve the desired objective. Taking this action will alter the state of the environment. In the simplest case, the state change will correspond to a modification of the beliefs associated with the random variables within the Bayesian net. In more extreme cases, the change in state may force a change in the structure of the Bayesian net, thus requiring recomputation of the beliefs. Either way, the resulting state is used to select the next action, and the process continues iteratively.

Due to the large state space and the probabilistic view on whether or not certain features hold for a given scenario, the decision problem posed by information operations corresponds to a partially observable MDP (POMDP). A POMDP is defined by a set of states $\boldsymbol{S}$, a set of actions, $\boldsymbol{A}$, a set of transitions between states associated with a particular actions, $\boldsymbol{T}$, a set of probability distributions, $\boldsymbol{P}$, over the set $\boldsymbol{S}$, a cost function $c(s,a)$, a set of observations, $\boldsymbol{Z}$, and a set of probability distributions, $\boldsymbol{O}$ over the set $\boldsymbol{Z}$. The probability distributions, $\boldsymbol{P}$, determine the probability of transitioning from state s to state s', given action a. The probability distributions, $\boldsymbol{O}$, determine the probability of observing z in state s' after taking action a.

In the context of IO, since the current state is captured by value assignments for known random variables and probabilities associated with possible value assignments for unknown random variables, the underlying decision process is partially observable. Key to addressing partial observability is the concept of the belief state (Kaelbling, Littman, & Cassandra 1998). A belief state is defined to be a probability distribution over the set of states, $\boldsymbol{S}$. In the case where the state estimation is given by a Bayesian network, the belief update process will correspond to propagating evidence through the network to revise the specific beliefs of the random variables.

Given a representation for a belief state, the POMDP can be cast as a continuous state-space MDP as follows. Define POMDP to have a set of belief states, $\boldsymbol{B}$, a set of actions, $\boldsymbol{A}$ (as before), a cost function, $\chi(b,a) = \sum_{s\in \boldsymbol{S}} b(s)c(s,a)$, and a set of transition probabilities defined by

$$\begin{aligned}\tau(b,a,b') &= \Pr(b' \mid a,b) \\ &= \sum_{z\in \boldsymbol{Z}} \Pr(b' \mid a,b,z)\Pr(z \mid a,b)\end{aligned}$$

where

$$\Pr(b' \mid b,a,z) = \begin{cases} 1\,;\text{if } \mathrm{BN}(b,a,z) = b' \\ 0\,;\text{otherwise} \end{cases}$$

for the belief net represented by BN(b, a, z). Since the belief captures all information known about the state so far, even if the underlying decision process is non-Markovian, the modified decision process utilizing these belief states is Markovian. Consequently, any technique for solving continuous state-space MDPs can now be applied (such as the temporal difference approach described earlier).

At this point, the major issue becomes representation of the belief state. Specifically, two issues must be addressed: the dimensionality of the state space and the continuous nature of the belief space. Considering the dimensionality problem, a naïve approach would involve directly mapping the random variables and the associated probabilities of their values to a belief state vector. For example, consider a simple Bayesian network with five random variables. For simplicity, assume each variable is a Boolean variable (i.e., either true or false). Assume we have knowledge about nodes A and B that enable us to derive probabilities for C, D, and E. Then the belief state could be represented in one of three ways.

1. $\{\Pr(A), \Pr(B), \Pr(C), \Pr(\neg C), \Pr(D), \Pr(\neg D), \Pr(E), \Pr(\neg E)\}$
2. $\{\arg\max\{\Pr(A)\}, \arg\max\{\Pr(B)\}, \arg\max\{\Pr(C)\}, \arg\max\{\Pr(D)\}, \arg\max\{\Pr(E)\}\}$
3. $\{\langle\arg\max\{\Pr(A)\}, \Pr(A)\rangle, \langle\arg\max\{\Pr(B)\}, \Pr(B)\rangle, \langle\arg\max\{\Pr(C)\}, \Pr(C)\rangle, \langle\arg\max\{\Pr(D)\}, \Pr(D)\rangle, \langle\arg\max\{\Pr(E)\}, \Pr(E)\rangle\}$

The first form simply represents the probabilities of each of the values for each of the random variables. The second assigns a vector based on the Bayes decision criterion (i.e, select the value with the maximum probability). The third is the same as the second except that it also includes the probabilities.

Note that the first representation is the most explicit and, thereby, the most complex. The second representation is much simpler in that it is no longer infinite; however, a significant amount of information is lost by discarding the probabilities. The third representation provides a compromise between the first and second; however, this representation does not simplify the state space. It seems clear that some form of compaction is required such as that provided by various feature selection methods (Wettschereck, *et al.*, 1997).

The second issue focuses on the problem of a continuous state space. Kaelbling, Littman, and Cassandra (1998) address this issue using their "witness" algorithm to construct policy trees based on dominance properties of the underlying policies. Unfortunately, even with clever approaches to pruning the space of policy trees, the approach still requires time exponential in the size of the observation space. Another approach involves constructing a Bayesian network between belief states and representing the conditional probability tables and reward functions using decision trees (Boutilier and Poole 1996). Value iteration is then applied to the decision trees to learn the optimal value functions and is, again, computationally intractable.

The reason for the computational complexity is that both of these approaches focus on computing an exact solution to the POMDP. Substantial savings can occur, however, when settling for an approximate solution. As already discussed, one of the most successful approximate solution methods for MDPs in high-dimensional state spaces is the temporal difference neural network, which has been used in very large state spaces to learn strong, near-optimal policies (Tesauro 1992).

Generality of the Framework

Learning approaches such as those described in the reinforcement learning community are called "model-free" because they require no specific model of the underlying Markov decision process. In some ways, this leads to added complexity in that the model must be learned from experience. On the other hand, this assumption provides tremendous power in the ability to adapt the process if environmental elements, sensors, or attack tactics change. Specifically, the details of the control elements are abstracted out of the control model; therefore, it is a simple matter to replace the controller with a new controller should the problem change. A neural network can be represented entirely by data (as a set of matrices of weights). Thus no software modification would be required except in mapping inputs and outputs to the appropriate nodes in the network.

Suppose the environment changes but the inputs and outputs remain the same. The only difference to the controller will be the feedback signal (i.e., the payoff) from the environment. Presumably, the new environment will not yield significantly different signals unless there is either a radical change in the task to be performed. In any event, the temporal difference method will accept the new feedback signal and begin to modify its model of the environment immediately.

Adaptation becomes more complicated if the inputs or the outputs change. Since the impact is similar, we will treat both of these situations together. When using a neural network, both the input data and the control data being recommended are represented by numerical input/output in the network. Changes mean that the inputs/outputs must be modified either through inserting a new node, deleting an existing node, or changing a node. Note that changing a node is analogous to a deletion followed by an insertion. If a change is of a similar type, it might make sense to use the original weights as a starting point; otherwise, the weights can be reinitialized for the new node. In all cases, it is prudent to retrain the network in the simulated environment before hosting in the controller. The advantage to this iterative approach is that it can bootstrap off of previously learned information.

Conclusion

Overall, the framework described in this paper is very flexible and powerful. It is flexible in its ability to abstract needed information from the environment and in its ability to be encapsulated from the environment. It is powerful in that it supports a wide variety of capabilities including feature extraction, function approximation, and adaptive control. The algorithms discussed in this paper are not the only ones possible and are offered as representative examples rather than design decisions. In the end, however, it is felt that adaptive approaches such as those offered above will offer superior power and flexibility over scripting or static rule-based reasoning.

References

Barto, A., Bradtke, S., and Singh, S. 1995. "Learning to Act Using Real-Time Dynamic Programming," *Artificial Intelligence*, Special Volume: Computational Research on Interaction and Agency, 72(1): 81–138.

Bellman, R. 1957. *Dynamic Programming*, Princeton, NJ: Princeton University Press.

Boutilier, C., and Poole, D. 1996. "Computing Optimal Policies for Partially Observable Decision Processes Using Compact Representations," *Proceedings of the 13th National Conference on Artificial Intelligence*, AAAI Press, pp. 1168–1175.

Kaelbling, L., Littman, M., and Cassandra, A. 1998. "Planning and Acting in Partially Observable Stochastic Domains," *Artificial Intelligence*, to appear.

Pearl, J. 1988. *Probabilistic Reasoning in Intelligent Systems*, San Mateo, CA: Morgan Kaufmann.

Rumelhart, D., Hinton, G., and Williams, R. 1986. "Learning Internal Representations by Error Propagation," *Parallel Distributed Processing: Explorations in the Microstructures of Cognition*, Vol. 1, D Rumelhart and J. McClelland (Eds.), Cambridge, MA: The MIT Press, pp. 318–362.

Sheppard, J. 1997. *Multi-Agent Reinforcement Learning in Markov Games*, Ph.D. Dissertation, Department of Computer Science, The Johns Hopkins University, Baltimore, MD.

Sheppard, J. 1998. "Co-Learning in Differential Games," *Machine Learning*, special issue on multi-agent learning, Vol. 33, No. 2/3, pp. 201–233.

Sutton, R. 1988. "Learning to Predict by Methods of Temporal Differences," *Machine Learning*, 3:9–44.

Tesauro, G. 1992. "Practical Issues in Temporal Difference Learning," *Machine Learning*, Vol. 8, pp. 257–277.

Von Stengel, B. 1998. "Computing Equilibria for Two-Person Games," *Handbook of Game Theory*, R. Aumann and S. Hart (eds.) Vol. 3, North-Holland, Amsterdam.

Wettschereck, D., Aha, D., and Mohri, T. 1997. "A Review and Empirical Evaluation of Feature Weighting Methods for a Class of Learning Algorithms," *Artificial Intelligence Review*, Vol. 11, pp. 273–314.

INFORMATION SUPERIORITY THROUGH INTELLIGENT INFORMATION OPERATIONS

Dr. John W. Sheppard
ARINC
2551 Riva Road
Annapolis, MD 21401
jsheppar@arinc.com

Abstract

The information revolution has created the ability for creating powerful tools to support the warfighter. Tools for collecting, analyzing, and communicating information are being created to improve the efficiency and efficacy of conducting military operations. Unfortunately, the same information revolution has introduced new vulnerabilities whereby adversaries can acquire, exploit, deny, or destroy information needed to support mission objectives. Information warfare has emerged to provide a new wave of warfare in which the focus has shifted from massive destruction of enemy physical assets to surgical attack on information assets. In this paper, we present a framework for supporting information warfare and information operations using advanced techniques from artificial intelligence and control theory. Specifically, we discuss the combination of techniques from approximate reasoning, dynamic programming, and game theory to define a capability to support the conduct of information operations.

Introduction

Information systems have become an essential element of military, government, commercial, and academic operation. The proliferation of computers, networks, and related technologies has provided the capability to rapidly collect, store, analyze, and disseminate information for a variety of purposes. The expediency, efficiency, productivity, and profitability of organizations and individuals have been significantly enhanced by this information revolution. The military especially benefits from this progress by providing decision makers unprecedented quantity, quality, and timeliness of information. The commander with the ability to know the order of battle, analyze events, and distribute critical information possesses a powerful advantage.

The benefits afforded by the information revolution are balanced by some problems. Information is a potent weapon and a lucrative target. The environment in which information is disseminated and stored provides a means for unauthorized access and manipulation. Nations, groups, and individuals seek to acquire, exploit, and protect information in support of their objectives. This exploitation and protection of information can occur for economic and political reasons as well as for military advantage. Strategies, both offensive and defensive, are being formulated to address actions involving the denial, exploitation, corruption, and destruction of enemy information. These strategies form the core of Information Operations (IO) and Information Warfare (IW).

In this paper, we discuss a framework for supporting a C3/C4 analyst in information operations. To understand where such a capability will benefit the analyst, we review the concept of the command and control decision and execution cycle, also known as the "OODA Loop." The OODA loop consists of four distinct phases corresponding, respectively, to *observe*, *orient*, *decide*, and *act*.

The first phase of the OODA loop is the observation phase. At this point, the analyst or command collects information about the battlespace (i.e., environment) within which information operations will occur. Typically, observation is constrained to data collection from sensors and any processing necessary to support the assessment of the information in the next phase. The second phase is orientation. In this phase, the analyst or commander interprets the information for situation assessment. At this point, inferences are drawn from the information that has been inferred to predict additional attributes about the situation (e.g., risk and strategy). In the third phase, decision, the commander evaluates the results of situation assessment and decides on an appropriate course of action. The resulting orders are passed to those who will execute the orders in the fourth phase, action.

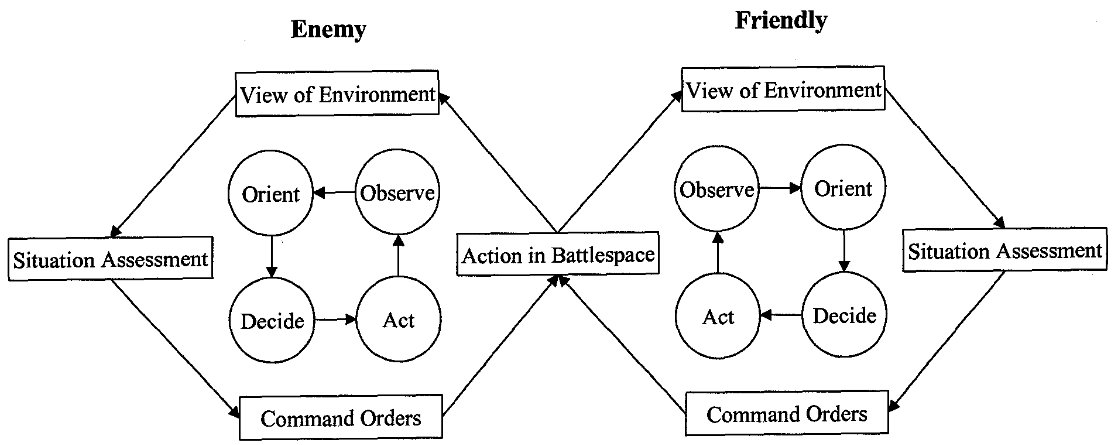


Figure 1. Interacting Decision and Execution Cycles.

Tools supporting the IO process must work within the decision and execution cycle, as shown in the OODA Loop. Specifically, through the intelligence process, data and information are collected about the target system and the processes that use that system. The intelligence process is responsible for collecting information both in support of planning and real-time execution. Therefore, the information to be observed must be stored in a database or made available as collected. Next, tools need to be able to query relevant information related to the current state and infer situation attributes as describe above. Several techniques exist for performing such inference, and we will suggest a particular approach later in this paper. Given the inferred situation, tools must be capable of assessing the available options in the light of the intended goal, the confidence in the current view of the environment, and the expected utility of executing any of the options. Finally, resulting actions must be reflected in the view of the environment, either through prediction of impact or through the collection of additional information (or both).

To ensure accurate representation and analysis of opponent capabilities in supporting the IO decision process, the opponent's corresponding decision process should be included. This can be represented as an interaction of two OODA loops (Figure 1). Since both cycles affect the environment, the friendly decision process should take into account the enemy's decision cycle to predict expected outcome. This results in the interacting decision cycles being represented as a "game," and techniques from game analysis need to be incorporated into the decision aid.

In a game, three major processes take place that coincide with the OOD phases of the OODA Loop (Figure 2). First, data and information are collected from the environment about the target or opponent. This information is used to capture a current "state" of the game and is combined with previously collected data and information to characterize the entire environment. Such characterization may consist of drawing inferences from known information to estimate or predict unknown attributes of the environment. The combination of known and inferred information defines the current "belief state" of the game. The belief state is used, in combination with a specific objective, to select a course of action for achieving the objective. Once the action is taken, the state of the environment changes, and the process repeats.

A Control-Theory View of Information Operations

In general, information operations (and the OODA loop) can be viewed as a special form of feedback (or closed loop) control where desired environment states are obtained by modifying control variables given the current state (Atekson, *et al.*, 1997). Typically, control systems are modeled in one of two ways—through forward models or through inverse models. A forward model uses the current state and the actions that can be applied in that state to predict the results of the actions (i.e., the next state). Typically, this is represented as $s(t+1) = f(s(t),a)$. An inverse model, on the other hand, provides an action given the current state and the desired "outcome," which may be the next state. Thus, the inverse model can be represented as $a = f(s(t),s(t+1))$.

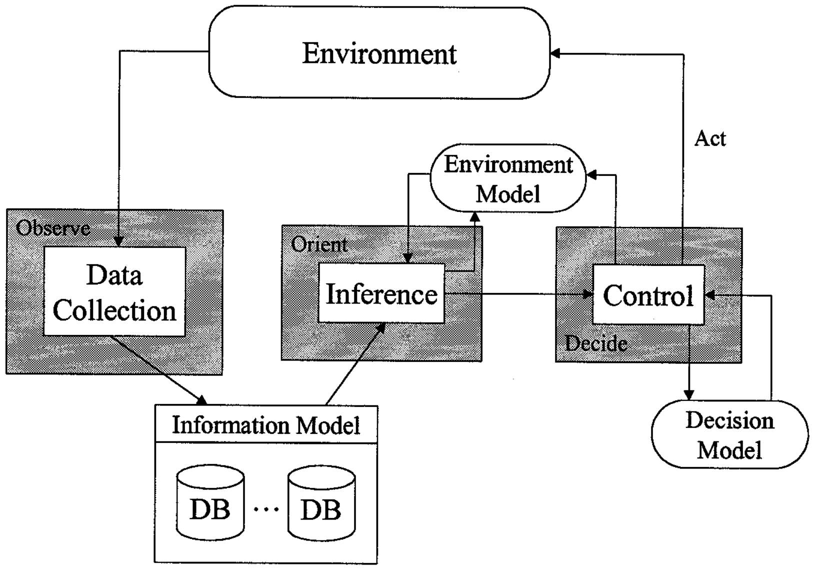


Figure 2. Intelligent IO Process Flow

Alternatively, rather than using the next state as an explicit parameter in the model, an expected payoff, ρ, (e.g., probability of kill) can be used in the models. Then the forward model becomes $\rho = f(s(t),a)$ and the inverse model becomes $a = f(s(t),\rho)$. Using this alternative form, the feedback control problem can be posed as the problem of optimizing the expected payoff for the controller.

The controller contains a "model" of the process being controlled. This may be an explicit model (e.g., a set of differential equations) or an implicit model (e.g., a neural network or lookup table matching states to actions). In the context of intelligent control, it is expected that the controller will process and modify an implicit model since such a model is both computationally efficient and relatively easy to modify based on past experience.

Once the controller determines the proper action to take (based on a control policy that is either stored or computed), the action is translated into appropriate commands or signals for actions to be taken in the environment. In the following sections, we will discuss one possible framework for implementing this architecture.

Markov Decision Processes

The most common form of representation for the types of decision problems outlined above is the *Markov decision process* (Barto, *et al.*, 1995). A Markov decision process (MDP) is defined by a set of states, $\boldsymbol{S}$, a set of actions, $\boldsymbol{A}$, a set of transitions between states, $\boldsymbol{T}$, associated with a particular action, and a set of discrete probability distributions, $\boldsymbol{P}$, over the set $\boldsymbol{S}$. Similarly, $\boldsymbol{T} : \boldsymbol{S} \times \boldsymbol{A} \rightarrow \boldsymbol{P}$. Associated with each action while in a given state is a cost (or reward), $c(s,a)$. Given an MDP, the goal is to determine a policy, $\pi(s)$, (i.e., a set of actions to be applied from a given state) to minimize total expected discounted cost.

Let $f^{\pi}(s_i)$ represent the total expected discounted infinite horizon cost under policy π from state s_i. Let γ $(0 \leq \gamma \leq 1)$ be a discount factor, having the effect of controlling the influence of future cost on π. Then,

$$f^{\pi}(s_i) = E_{\pi}\left[\sum_{t=0}^{\infty} \gamma^t c(s_t, \pi(s_t)) \mid s_0 = s_i\right]$$

where $E_\pi[\bullet]$ is the expectation given policy π. We can estimate $f^\pi(s_i)$ for some $\pi(s_i) = a$ as follows:

$$f^\pi(s_i) \approx Q^f(s_i a) = c(s_i, a) + \gamma \sum_{s_j \in \mathbf{S}} p(s_j \mid s_i, a) f(s_j)$$

From this, we are able to establish policy, π, based on the current estimate Q^f; namely, select $\pi(s_i) = a$ such that,

$$Q^{f_i}(s_i, \pi(s_i)) = \min_{a \in \mathbf{A}} Q^f(s_i, a).$$

This equation is in the form of the *Bellman optimality equation* which can be solved for $f(s_j)$ using several techniques such as dynamic programming (Bellman, 1957).

With the combined OODA loop as depicted in Figure 1, we can generalize the development of a policy within the context of *Markov games* (Sheppard, 1997; Sheppard, 1998). A Markov game is an extension of the MDP in which decisions by multiple players must be considered, and these decisions generally conflict. Under the restriction of two-person games, we define $\boldsymbol{S}$ to be a set of states, $\boldsymbol{A}_1$ and $\boldsymbol{A}_2$ to be sets of actions for players 1 and 2 respectively, and $\boldsymbol{T}$ to be a set of transitions similar to the MDP, such that $\boldsymbol{T} : \boldsymbol{S} \times \boldsymbol{A}_1 \times \boldsymbol{A}_2 \to \boldsymbol{P}$. Associated with each player is a cost (or reward) function, $c_1(s,a_1,a_2)$ and $c_2(s,a_1,a_2)$.

In the context of IO, the objective is to find a policy $\pi_1(s)$ that maximizes total expected discounted reward in the presence of an opposing policy $\pi_2(s)$. Value functions for each player analogous to the MDP case can be determined. For alternating games (which is unlikely), policies can be determined for each player given their value functions using minimax. In the event simultaneous games are being played, mixed strategies may be required. For zero-sum games, policies at individual states can be determined using linear programming (Sheppard, 1997). For non-zero-sum games (which would result when the value functions for the two players are not complementary), a linear complementarity problem can be constructed and solved using various numeric techniques such as the Lemke-Howson algorithm (von Stengel, 1998).

Implicit Models of MDPs and Markov Games

Given the large state space of the IO scenario, it is likely that a traditional approach using dynamic programming to solve these MDPs will be infeasible. As a result, some form of function approximation will be required for generalizing from representative state-action pairs to the full range of state-action possibilities. One of the more common approaches to function approximation is the use of feed-forward neural networks.

The traditional feed-forward neural network calculates the output of a given node, O_j as $O_j = \sum_{i=1}^{n} w_{ji} x_i$, where n is the number of inputs to the current node. Learning consists of modifying the weights, w_{ji} in such a way to reduce the network error (calculated as $E = \frac{1}{2}(z - O)^2$, where z is the expected network output and O is the actual network output). This weight update (called backpropagation) is accomplished by determining the gradient of the error surface and modifying the weights in the direction of the gradient. Specifically, the weight update rule for backpropagation can be represented as $\Delta w_{ji} = \alpha(z - O)\nabla_w O$ (Rumelhart *et al.*, 1986).

The standard backpropagation algorithm, while performing well on classification tasks, has been shown to have difficulties solving highly dynamic problems such as control problems. In response to these difficulties, work in reinforcement learning and neural networks resulted in the development of a class of algorithms capable of solving specific types of control problems. In particular, *temporal difference* algorithms have been shown to solve highly complex control problems that are posed as MDPs.

Rich Sutton developed an algorithm for training feed-forward neural networks to solve control tasks that can be modeled as an MDP (Sutton, 1988). Sutton's temporal difference method focuses on the problem of predicting expected discounted payoff from a given state. This method is applied in "multi-step prediction problems" where

payoff is not awarded until several steps after a prediction for payoff is made. At each step, the controller predicts what its future payoff will be, based on several available actions, and chooses its action based on that prediction. However, the ramifications for taking the sequence of actions are not revealed until (typically) the end of the process.

According to Sutton, the temporal difference method is an extension of the prototypical supervised learning rule that is based on gradient descent (as described above). If we assume a prediction depends upon a vector of modifiable weights w, and a vector of state variables s, then supervised learning uses a set of paired state vectors and actual outcomes to modify the weights to reduce the error between the predictions and the known outcomes.

The standard, supervised learning method works best for single-step prediction problems. For multi-step prediction, the vector w cannot be updated until the end of the sequence, and all observations and predictions must be remembered until the end of the sequence. Sutton's temporal difference method permits incremental update and is based on the observation that

$$z - P_t = \sum_{k=t}^{m} (P_{k+1} - P_k)$$

where P_t is the predicted payoff at time t, m is the number of steps in the sequence, and $P_{m+1} = z$. In this case, the supervised learning rule becomes

$$\Delta w_{ji}^{t} = \alpha(P_{t+1} - P_t)\sum_{k=1}^{t} \nabla_w P_k .$$

This update can be computed incrementally because it depends only on a pair of successive predictions (P_t and P_{t+1}) and on the sum of past values for $\nabla_w P_t$.

Sutton goes on to describe a family of temporal difference methods based on the influence past updates have on the current update of the weight vector. These methods are based on a parameter, $\lambda \in [0,1]$, which specifies a discount factor in the prediction equation. Sutton refers to this family of equations as the TD(λ) family. When $\lambda = 0$, past updates have no influence on the current update. When $\lambda = 1$, all past predictions receive equal weight. Assuming it is desirable for the update procedure to be more sensitive to recent predictions than to distant predictions, the changes are weighted according to λ^k. Thus the update equation becomes

$$\Delta w_{ji}^{t} = \alpha(P_{t+1} - P_t)\sum_{k=1}^{t} \lambda^{t-k} \nabla_w P_k .$$

Note this equation (and the original gradient descent equation) assumes a single linear combination of weights. This means that for a function to be learned, that function must itself be linear in the inputs (i.e., underlying concepts must be linearly separable). This limitation can be addressed by using the generalized delta rule as described in (Rumelhart *et al.*, 1986).

Modeling Belief States with Bayesian Networks

Given a neural network for computing a value function, we need a method of representing the state of the control problem being solved. For the IO problem, we suggest using a Bayesian network to capture the current belief in the state of the network under attack. A Bayesian network is a network where the nodes correspond to random variables and directed edges correspond to dependence (i.e., causal) relationships between the random variables (Pearl, 1988).

Within the context of IO, a node in the network will correspond to some attribute of the environment. Expected values for these attributes are derived from known attributes of the environment (obtained through intelligence sources) and conditional probabilities of other values given certain known values within the environment. Using

basic operations from probability theory, given a Bayesian network and certain known data, probabilities can be propagated through the network to derive expectations for unknown attributes of the network.

Bayesian networks are constructed such that the "roots" of the network (defined to be those nodes that are conditioned on no other random variables) have "prior" probabilities associated with them. Interior nodes of the network have conditional probability tables associated with them indicating the probability of the variable taking on some value given a value of the ancestor nodes. In addition, the networks are constructed to be "acyclic" (i.e., no path exists through the network from a node back to the same node).

Combining Bayesian Networks and Markov Decision Processes

Key to determining a policy that solves a particular MDP is the proper representation of the state of the process. The IO scenario assumes the decision process corresponds to controlling the state of the environment until it reaches some desired state maximizing a particular objective function. Using this approach, we see that the Bayesian network captures the state of the environment. From the beginning of the attack scenario, we establish a "baseline" state using intelligence data, likely environmental conditions, and likely mission scenarios. Key attributes will be derived from the Bayesian network to form the actual state description for the Markov decision process. Note that this state need not represent the state of the entire environment. Such a state representation would be too massive to be able to process efficiently. Rather, the state representation will focus on the area of the environment of interest to the commander.

From the Bayesian network, an estimate of the current state will be formulated. Based on that state and a set of objectives to be achieved, feasible actions will be considered. The action selected will be one to maximize the ability to achieve the desired objective. Taking this action will alter the state of the environment. In the simplest case, the state change will correspond to a modification of the beliefs associated with the random variables within the Bayesian net. In more extreme cases, the change in state may force a change in the structure of the Bayesian net, thus requiring recomputation of the beliefs. Either way, the resulting state is used to select the next action, and the process continues iteratively.

Due to the large state space and the probabilistic view on whether or not certain features hold for a given scenario, the decision problem posed by information operations corresponds to a partially observable MDP (POMDP). A POMDP is defined by a set of states $\boldsymbol{S}$, a set of actions, $\boldsymbol{A}$, a set of transitions between states associated with a particular actions, $\boldsymbol{T}$, a set of probability distributions, $\boldsymbol{P}$, over the set $\boldsymbol{S}$, a cost function $c(s,a)$, a set of observations, $\boldsymbol{Z}$, and a set of probability distributions, $\boldsymbol{O}$ over the set $\boldsymbol{Z}$. The probability distributions, $\boldsymbol{P}$, determine the probability of transitioning from state s to state s', given action a. The probability distributions, $\boldsymbol{O}$, determine the probability of observing z in state s' after taking action a.

In the context of IO, since the current state is captured by value assignments for known random variables and probabilities associated with possible value assignments for unknown random variables, the underlying decision process is partially observable. Key to addressing partial observability is the concept of the belief state (Kaelbling, Littman, & Cassandra 1998). A belief state is defined to be a probability distribution over the set of states, $\boldsymbol{S}$. In the case where the state estimation is given by a Bayesian network, the belief update process will correspond to propagating evidence through the network to revise the specific beliefs of the random variables.

Given a representation for a belief state, the POMDP can be cast as a continuous state-space MDP as follows. Define POMDP to have a set of belief states, $\boldsymbol{B}$, a set of actions, $\boldsymbol{A}$ (as before), a cost function, $\chi(b,a) = \sum_{s \in \boldsymbol{S}} b(s)c(s,a)$, and a set of transition probabilities defined by

$$\begin{aligned}\tau(b,a,b') &= \Pr(b' \mid a,b) \\ &= \sum_{z \in \boldsymbol{Z}} \Pr(b' \mid a,b,z)\Pr(z \mid a,b)\end{aligned}$$

where

$$\Pr(b' \mid b, a, z) = \begin{cases} 1\,; \text{if } \mathrm{BN}(b, a, z) = b' \\ 0\,; \text{otherwise} \end{cases}$$

for the belief net represented by BN(b, a, z). Since the belief captures all information known about the state so far, even if the underlying decision process is non-Markovian, the modified decision process utilizing these belief states is Markovian. Consequently, any technique for solving continuous state-space MDPs can now be applied (such as the temporal difference approach described earlier).

At this point, the major issue becomes representation of the belief state. Specifically, two issues must be addressed: the dimensionality of the state space and the continuous nature of the belief space. Considering the dimensionality problem, a naïve approach would involve directly mapping the random variables and the associated probabilities of their values to a belief state vector. For example, consider a simple Bayesian network with five random variables. For simplicity, assume each variable is a Boolean variable (i.e., either true or false). Assume we have knowledge about nodes A and B that enable us to derive probabilities for C, D, and E. Then the belief state could be represented in one of three ways.

1. $\{\Pr(A), \Pr(B), \Pr(C), \Pr(\neg C), \Pr(D), \Pr(\neg D), \Pr(E), \Pr(\neg E)\}$
2. $\{\arg\max\{\Pr(A)\}, \arg\max\{\Pr(B)\}, \arg\max\{\Pr(C)\}, \arg\max\{\Pr(D)\}, \arg\max\{\Pr(E)\}\}$
3. $\{\langle \arg\max\{\Pr(A)\}, \Pr(A)\rangle, \langle \arg\max\{\Pr(B)\}, \Pr(B)\rangle, \langle \arg\max\{\Pr(C)\}, \Pr(C)\rangle, \langle \arg\max\{\Pr(D)\}, \Pr(D)\rangle, \langle \arg\max\{\Pr(E)\}, \Pr(E)\rangle\}$

The first form simply represents the probabilities of each of the values for each of the random variables. The second assigns a vector based on the Bayes decision criterion (i.e, select the value with the maximum probability). The third is the same as the second except that it also includes the probabilities.

Note that the first representation is the most explicit and, thereby, the most complex. The second representation is much simpler in that it is no longer infinite; however, a significant amount of information is lost by discarding the probabilities. The third representation provides a compromise between the first and second; however, this representation does not simplify the state space. It seems clear that some form of compaction is required such as that provided by various feature selection methods (Wettschereck, *et al.*, 1997).

The second issue focuses on the problem of a continuous state space. Kaelbling, Littman, and Cassandra (1998) address this issue using their "witness" algorithm to construct policy trees based on dominance properties of the underlying policies. Unfortunately, even with clever approaches to pruning the space of policy trees, the approach still requires time exponential in the size of the observation space. Another approach involves constructing a Bayesian network between belief states and representing the conditional probability tables and reward functions using decision trees (Boutilier and Poole 1996). Value iteration is then applied to the decision trees to learn the optimal value functions and is, again, computationally intractable.

The reason for the computational complexity is that both of these approaches focus on computing an exact solution to the POMDP. Substantial savings can occur, however, when settling for an approximate solution. As already discussed, one of the most successful approximate solution methods for MDPs in high-dimensional state spaces is the temporal difference neural network, which has been used in very large state spaces to learn strong, near-optimal policies (Tesauro 1992).

Generality of the Framework

Learning approaches such as those described in the reinforcement learning community are called "model-free" because they require no specific model of the underlying Markov decision process. In some ways, this leads to added complexity in that the model must be learned from experience. On the other hand, this assumption provides tremendous power in the ability to adapt the process if environmental elements, sensors, or attack tactics change. Specifically, the details of the control elements are abstracted out of the control model; therefore, it is a simple matter to replace the controller with a new controller should the problem change. A neural network can be represented entirely by data (as a set of matrices of weights). Thus no software modification would be required except in mapping inputs and outputs to the appropriate nodes in the network.

Suppose the environment changes but the inputs and outputs remain the same. The only difference to the controller will be the feedback signal (i.e., the payoff) from the environment. Presumably, the new environment will not yield significantly different signals unless there is either a radical change in the task to be performed. In any event, the temporal difference method will accept the new feedback signal and begin to modify its model of the environment immediately.

Adaptation becomes more complicated if the inputs or the outputs change. Since the impact is similar, we will treat both of these situations together. When using a neural network, both the input data and the control data being recommended are represented by numerical input/output in the network. Changes mean that the inputs/outputs must be modified either through inserting a new node, deleting an existing node, or changing a node. Note that changing a node is analogous to a deletion followed by an insertion. If a change is of a similar type, it might make sense to use the original weights as a starting point; otherwise, the weights can be reinitialized for the new node. In all cases, it is prudent to retrain the network in the simulated environment before hosting in the controller. The advantage to this iterative approach is that it can bootstrap off of previously learned information.

Conclusion

Overall, the framework described in this paper is very flexible and powerful. It is flexible in its ability to abstract needed information from the environment and in its ability to be encapsulated from the environment. It is powerful in that it supports a wide variety of capabilities including feature extraction, function approximation, and adaptive control. The algorithms discussed in this paper are not the only ones possible and are offered as representative examples rather than design decisions. In the end, however, it is felt that adaptive approaches such as those offered above will offer superior power and flexibility over scripting or static rule-based reasoning.

References

Barto, A., Bradtke, S., and Singh, S. 1995. "Learning to Act Using Real-Time Dynamic Programming," *Artificial Intelligence*, Special Volume: Computational Research on Interaction and Agency, 72(1): 81–138.

Bellman, R. 1957. *Dynamic Programming*, Princeton, NJ: Princeton University Press.

Boutilier, C., and Poole, D. 1996. "Computing Optimal Policies for Partially Observable Decision Processes Using Compact Representations," *Proceedings of the 13th National Conference on Artificial Intelligence*, AAAI Press, pp. 1168–1175.

Kaelbling, L., Littman, M., and Cassandra, A. 1998. "Planning and Acting in Partially Observable Stochastic Domains," *Artificial Intelligence*, to appear.

Pearl, J. 1988. *Probabilistic Reasoning in Intelligent Systems*, San Mateo, CA: Morgan Kaufmann.

Rumelhart, D., Hinton, G., and Williams, R. 1986. "Learning Internal Representations by Error Propagation," *Parallel Distributed Processing: Explorations in the Microstructures of Cognition*, Vol. 1, D Rumelhart and J. McClelland (Eds.), Cambridge, MA: The MIT Press, pp. 318–362.

Sheppard, J. 1997. *Multi-Agent Reinforcement Learning in Markov Games*, Ph.D. Dissertation, Department of Computer Science, The Johns Hopkins University, Baltimore, MD.

Sheppard, J. 1998. "Co-Learning in Differential Games," *Machine Learning*, special issue on multi-agent learning, Vol. 33, No. 2/3, pp. 201–233.

Sutton, R. 1988. "Learning to Predict by Methods of Temporal Differences," *Machine Learning*, 3:9–44.

Tesauro, G. 1992. "Practical Issues in Temporal Difference Learning," *Machine Learning*, Vol. 8, pp. 257–277.

Von Stengel, B. 1998. "Computing Equilibria for Two-Person Games," *Handbook of Game Theory*, R. Aumann and S. Hart (eds.) Vol. 3, North-Holland, Amsterdam.

Wettschereck, D., Aha, D., and Mohri, T. 1997. "A Review and Empirical Evaluation of Feature Weighting Methods for a Class of Learning Algorithms," *Artificial Intelligence Review*, Vol. 11, pp. 273–314.

The U. S. Army Prognostics Framework Research and Development

Dr. Li Pi Su

e-mail: lipisu@redstone.army.mil

Advanced Technology Office

The U.S. Army TMDE Activity

The U.S. Army Aviation and Missile Command

DSN: 788-8552 **Com: 256-842-8552**

PROGNOSTICS FRAMEWORK (PF) TEAM

- ***DR. LI PI SU, U. S. ARMY*** **(OVERSEES PF PROJECT TECHNICAL AND SYSTEM DVELOPMENT, TECHNOLOGY INSERTION)**
- ***MS. MARY NOLAN, GAC*** **(MANAGES PF SYSTEM DEVELOPMENT & COORDINATES WITH THE US ARMY LIA AND RELATED AGENCIES)**
- ***MR. GREG DEMARE, GAC*** **(CHIEF SOFTWARE ENGINEER**
- ***MR. DAVE CAREY, GAC*** **(CHIEF SYSTEM APPLICATION ENGINEER)**

PROGNOSTICS FRAMEWORK

IMPETUS

- No existing data available for predictive analyses
- No system-level diagnostic technology
- Most “diagnostics” are troubleshooting procedures
- Need to define requirements of predictive data
- No integrated diagnostics and prognostics technology

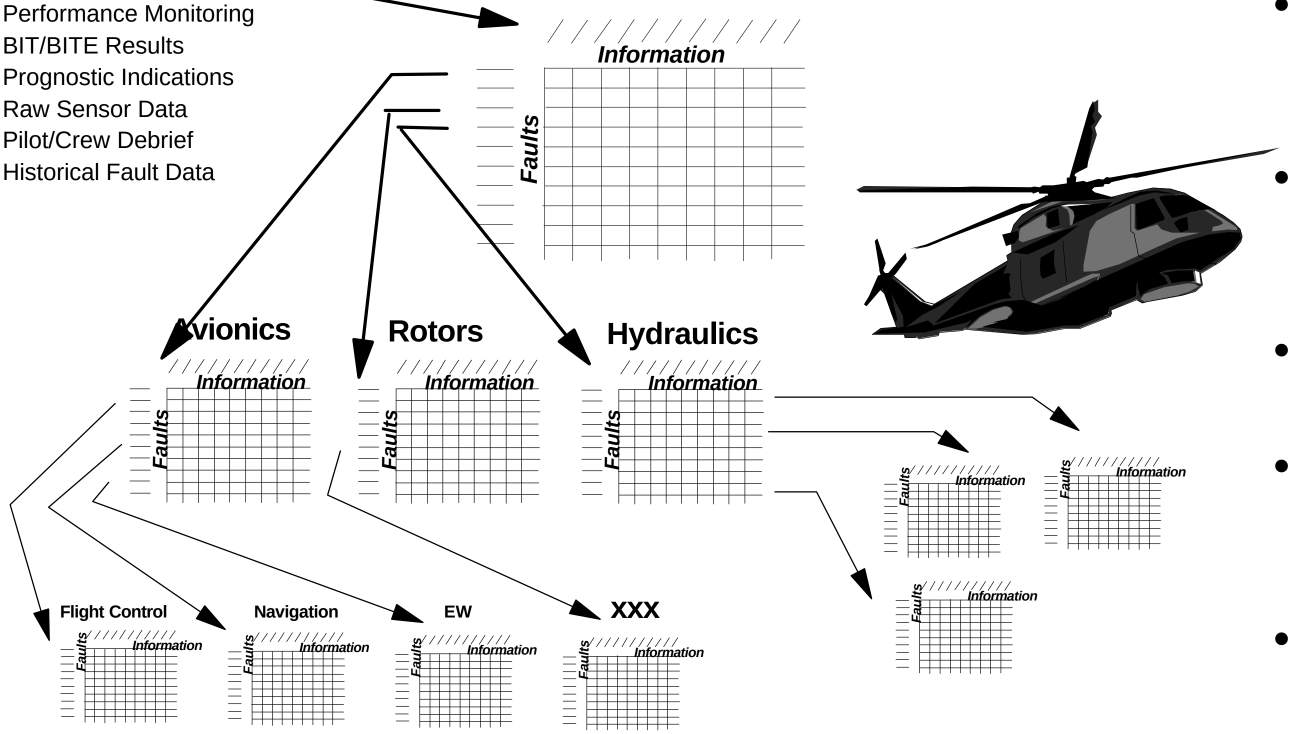
Why A Prognostics Framewo

- Point Solutions too Expensive; Risky (Outcome unsure)
- Generic, Tailorable Approach will save time, money, and program-specific funds; fastest way for Army to converge on Prognostics capability
- Information to be provided to operational & maintenance crew should be normalized/standardized across Army systems
- Prognostic Mechanisms at various stages of maturity; system-level implementations are non-existent
- Need to Tie-in to logistics infrastructure is critical (e.g., IETM, logistics planning, mission planning, spare parts provisioning)
- Prognostics should be integrated with Diagnostics to provide a total "Health Management Capability"

Why This Approach?

Diagnostician uses a design-based model of fault/symptom relationships to isolate faults

INFORMATION:
Operational Data
Performance Monitoring
BIT/BITE Results
Prognostic Indications
Raw Sensor Data
Pilot/Crew Debrief
Historical Fault Data



- **Open architecture; generically applicable**
- **Single knowledge base for embedded and off-line**
- **Software structure is extendible**
- **Hierarchical approach enables *<u>system integration</u>***
- **Can be used for legacy systems and new designs**

What is the Prognostics Framework?

- A *generic*, structured information architecture and tools to implement Prognostics by supporting
  - PMs in application of Prognostics
  - Operational Crew in Situational Awareness
  - Maintainers in Optimal Logistics Support
- Integrates current LIA TEDANN Program
- Can be applied to existing and new weapon systems
- Can be embedded or off-board
- Enables PMs to *Converge* on Prognostics as technology evolves
- Makes maximum use of existing Sensor/BIT data
- Automatically logs Historical Data

HTI

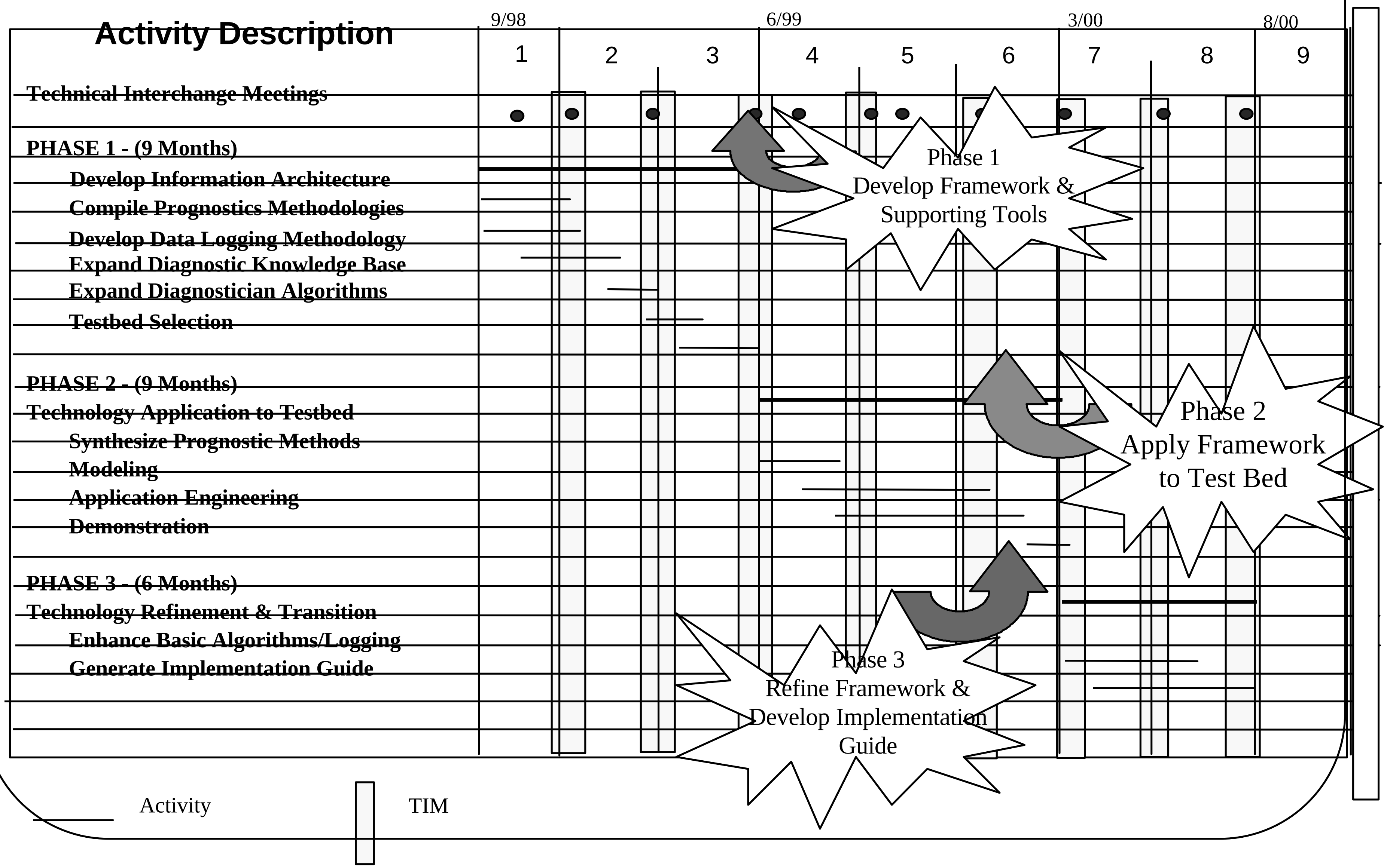
TEDANN

FAMPS

PFSA

[redacted]

Prognostics Framework Schedule



Prognostics Framework Architecture

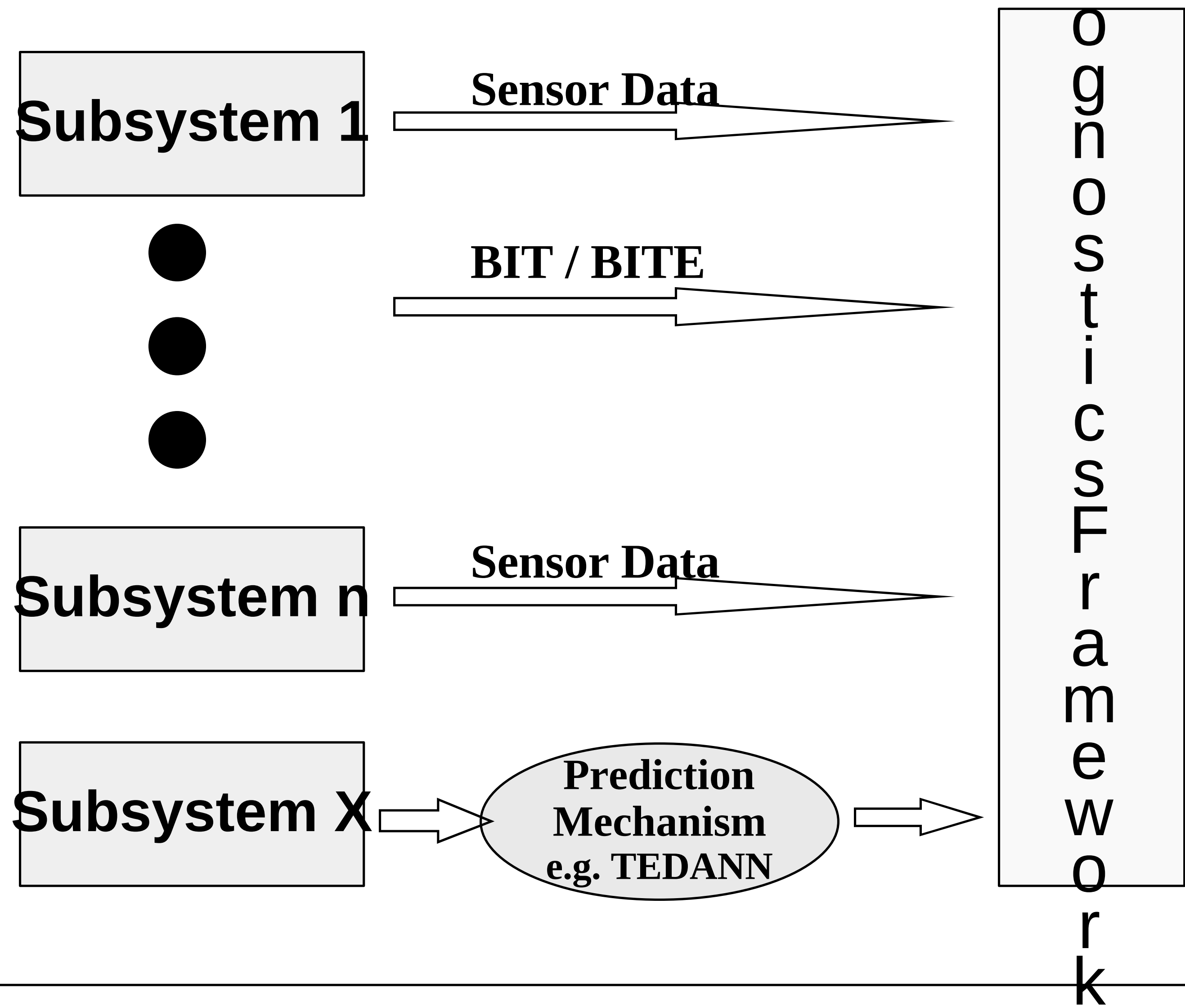
Prognostics Framework

Complements Other Prognostics Efforts

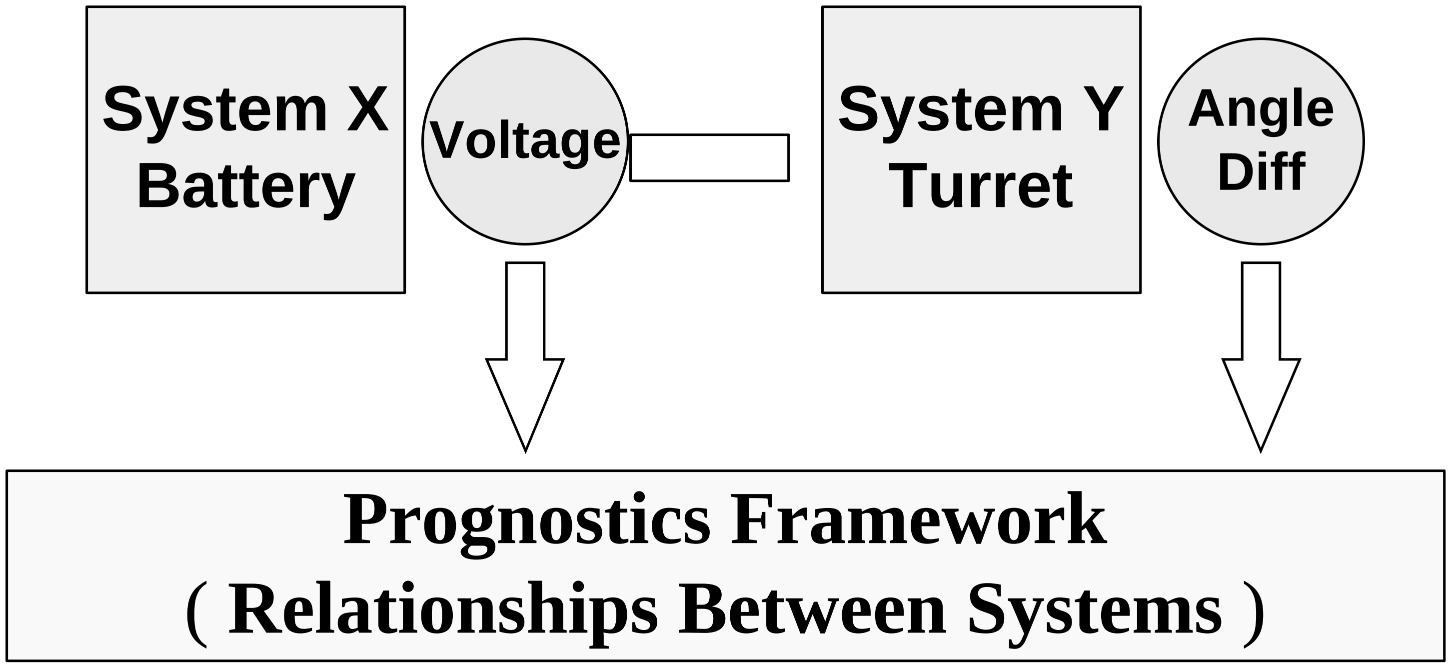
- Integrates Diagnostic/Prognostic Mechanism Outputs From Many Subsystems
- Provides Supplemental Prognostics
- Provides Diagnostic Analyses
- Ties-in to logistics infrastructure
- Prepares Information for Use By Both Operator & Maintainer

Prognostics Framework

Integrates Data From Many Subsystems



Prognostics Framework
Integrates Data From Many Subsystems



Voltage Low	**and**	**Angle Failure**	**=**	**Bad Battery**
Voltage Ok	**and**	**Angle Failure**	**=**	**Bad Turret**

Prognostics Framework
Provides Diagnostics and "Supplemental" Prognostics Analyses

Battery Voltage

Generator Output

●
●
●

System X Voltage

Clutch Pad Thickness

PrognosticsFramework

Prognostics Framework

PrognosticsFramewo

Prognostics Framework

Supports Operations and Maintenance

Missions

- **Mission Possible or Not**
- **Predicted Mission Success or Failure**

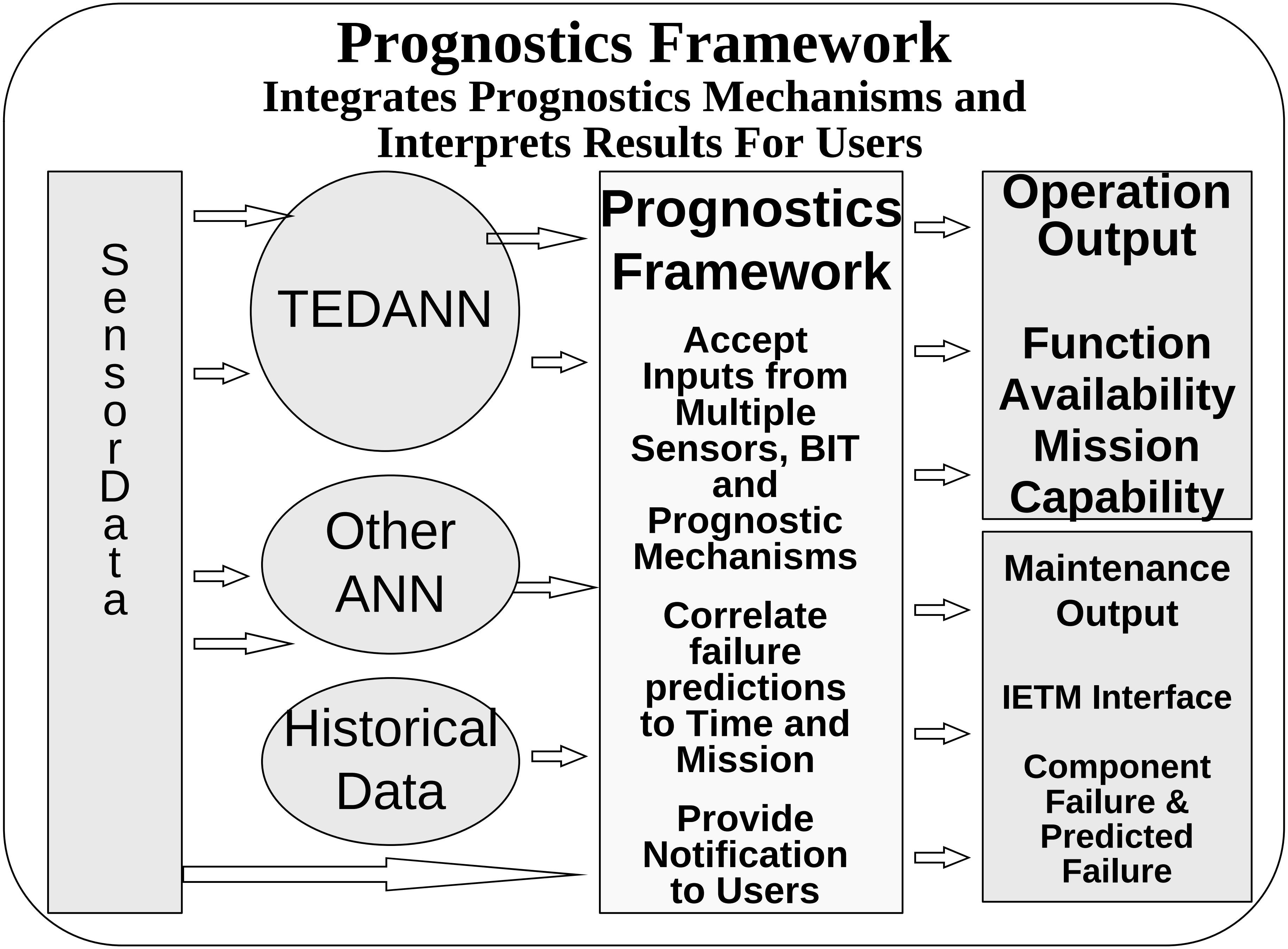
Operations

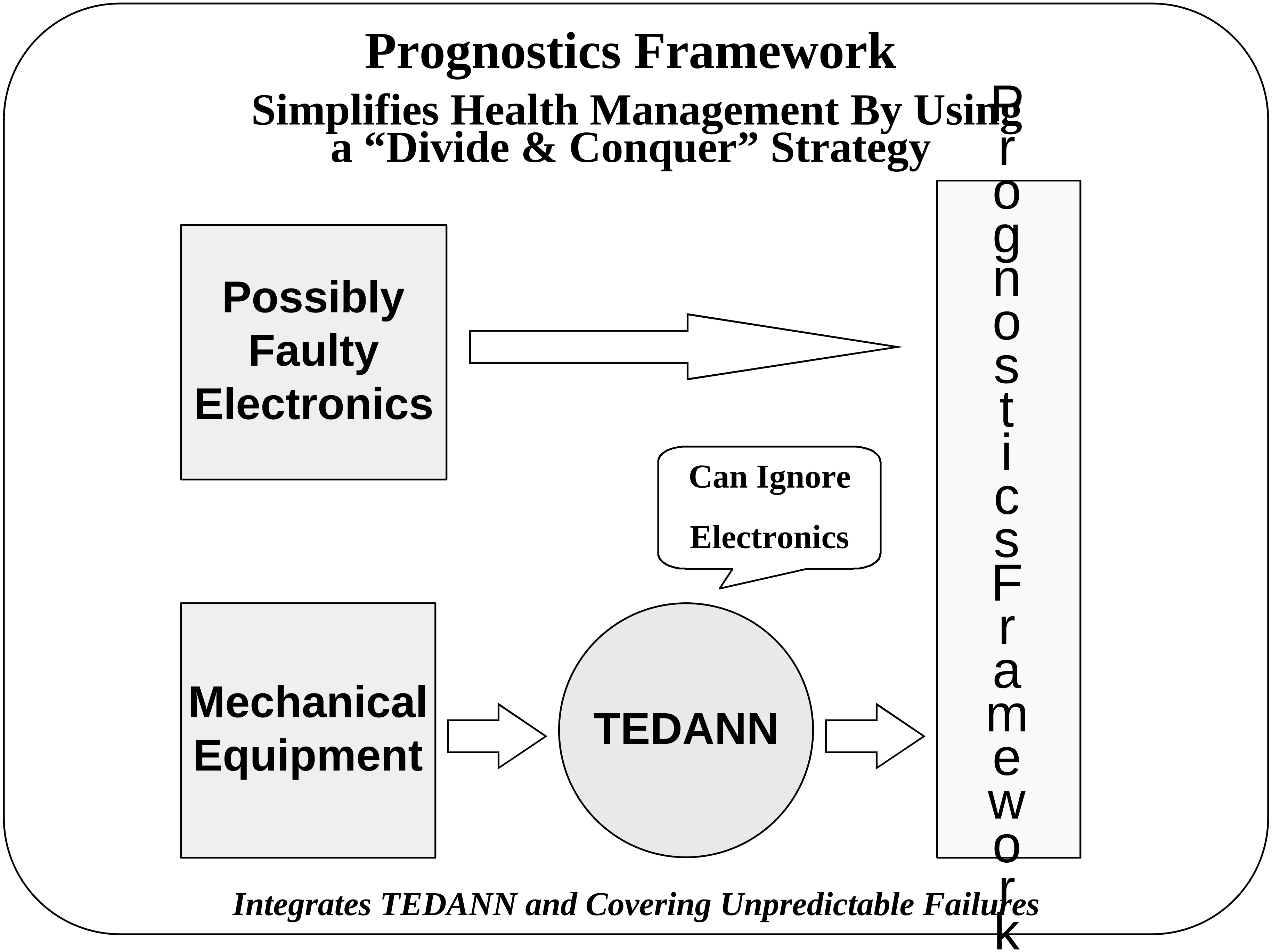
- **Functions Available/Unavailable**
- **Predicted Function Times To Failure**

Maintenance

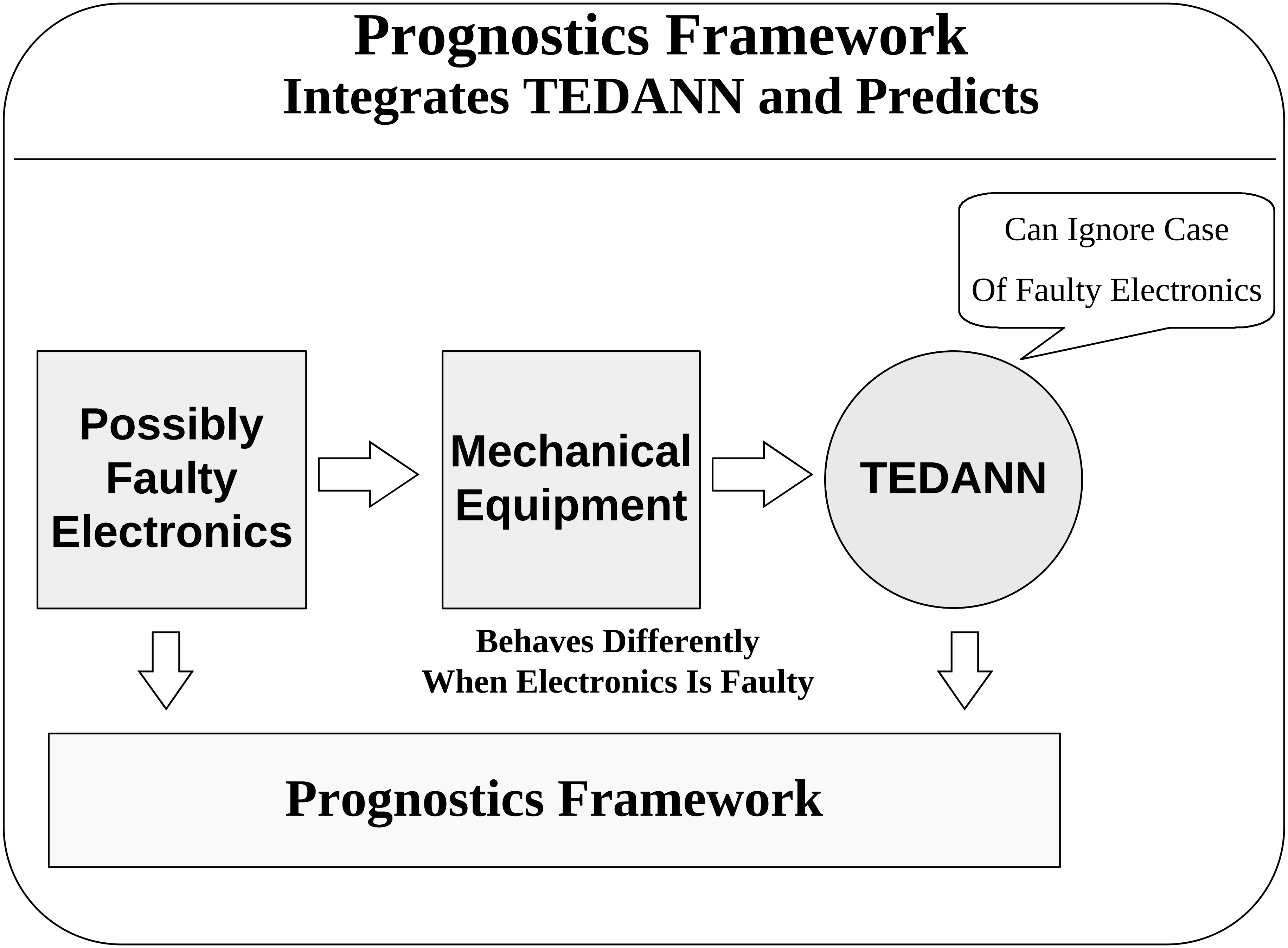
- **Components Requiring Repair**
- **Components Needing Repair Within Time Period X**
- **Spares & Tools Required for Fix**

Bottom Line: ***Increased Operational Readiness & Battlefield Situational Awareness***


Prognostics Framework
Integrates Prognostics Mechanisms and Interprets Results For Users
SensorData
TEDANN
Other ANN
Historical Data
Prognostics Framework
Accept Inputs from Multiple Sensors, BIT and Prognostic Mechanisms
Correlate failure predictions to Time and Mission
Provide Notification to Users
Operation Output
Function
Availability
Mission
Capability
Maintenance Output
IETM Interface
Component Failure & Predicted Failure



Prognostics Framework
Simplifies Health Management By Using a "Divide & Conquer" Strategy
Possibly Faulty Electronics
Can Ignore Electronics
Mechanical Equipment
TEDANN
PrognosticsFramework
Integrates TEDANN and Covering Unpredictable Failures


Prognostics Framework
Integrates TEDANN and Predicts
Can Ignore Case
Of Faulty Electronics
Possibly Faulty Electronics
Mechanical Equipment
TEDANN
Behaves Differently
When Electronics Is Faulty
Prognostics Framework

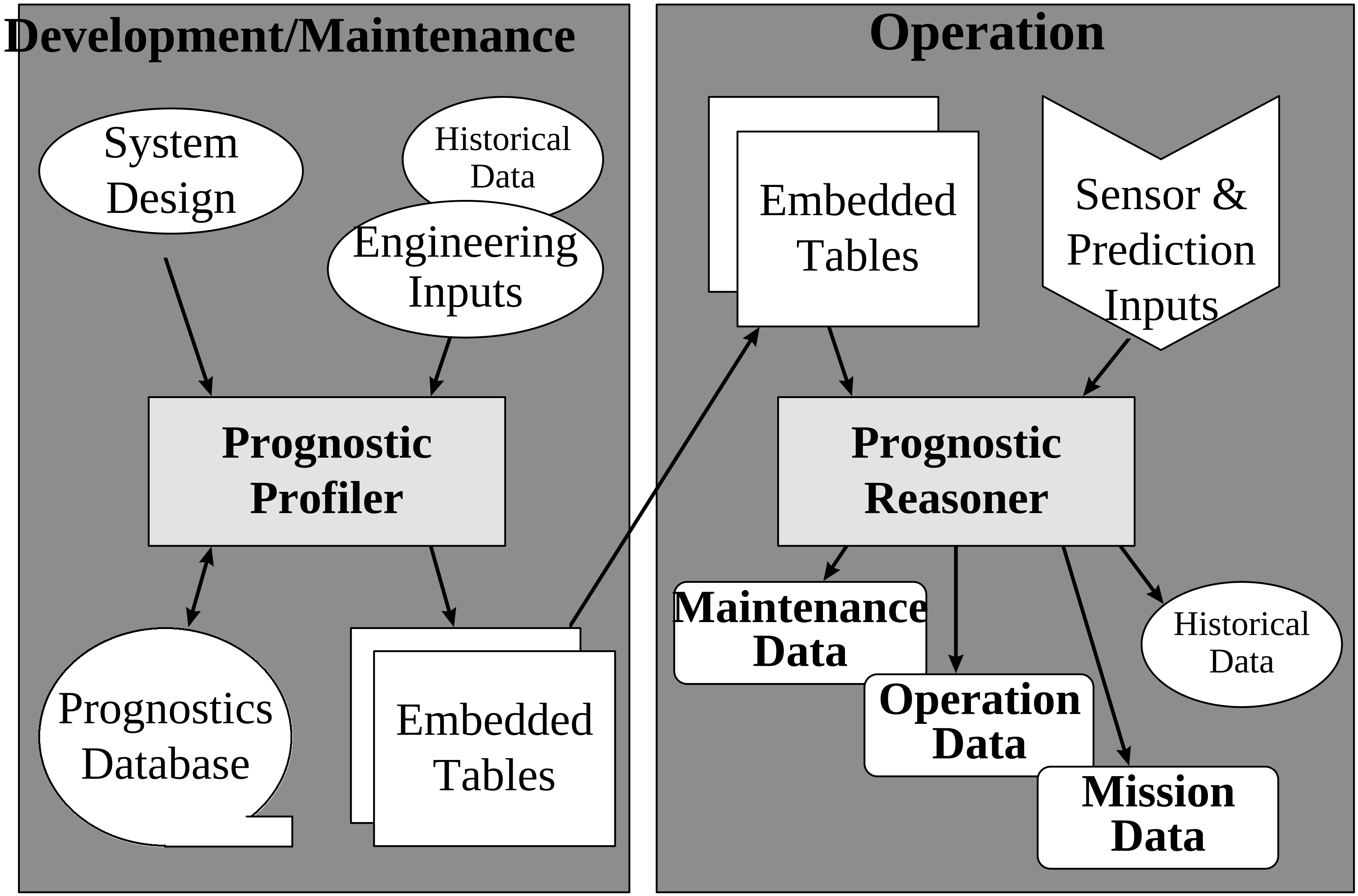
Prognostics Framework Design Approach

Prognostics Framework

Design Goals

- ❒Provide a Generic Solution to Prognostics Implementations
- ❒Open Architecture allows complementing and enhancing Existing and Future Prognostics Mechanisms
- ❒Minimize Cost of Development and Maintenance of Prognostics Framework Applications

Top Level Prognostics Framework Design



Prognostics Framework

Prognostics *Profiler* Software Module

Purpose: Support both development and maintenance of an operational Prognostics Framework System.

Design Goals: Provide Services for developing and maintaining an operational Prognostics Framework System that are easy to understand and to use.

Approach: Provide developer interfaces that are similar to the Diagnostic Profiler in feel but extending support to prognostics.

Prognostics Framework

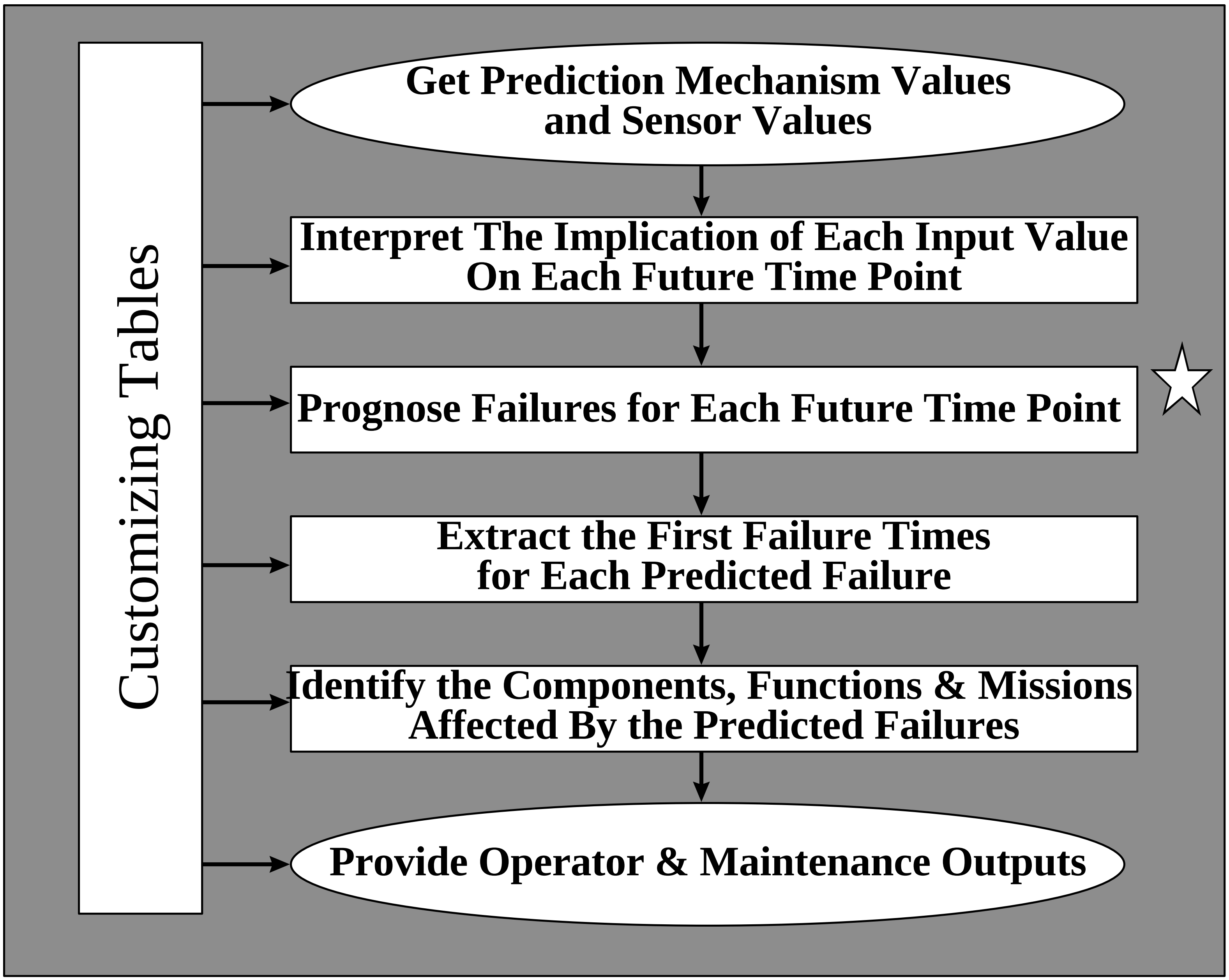
Prognostics *Reasoner* Software Module

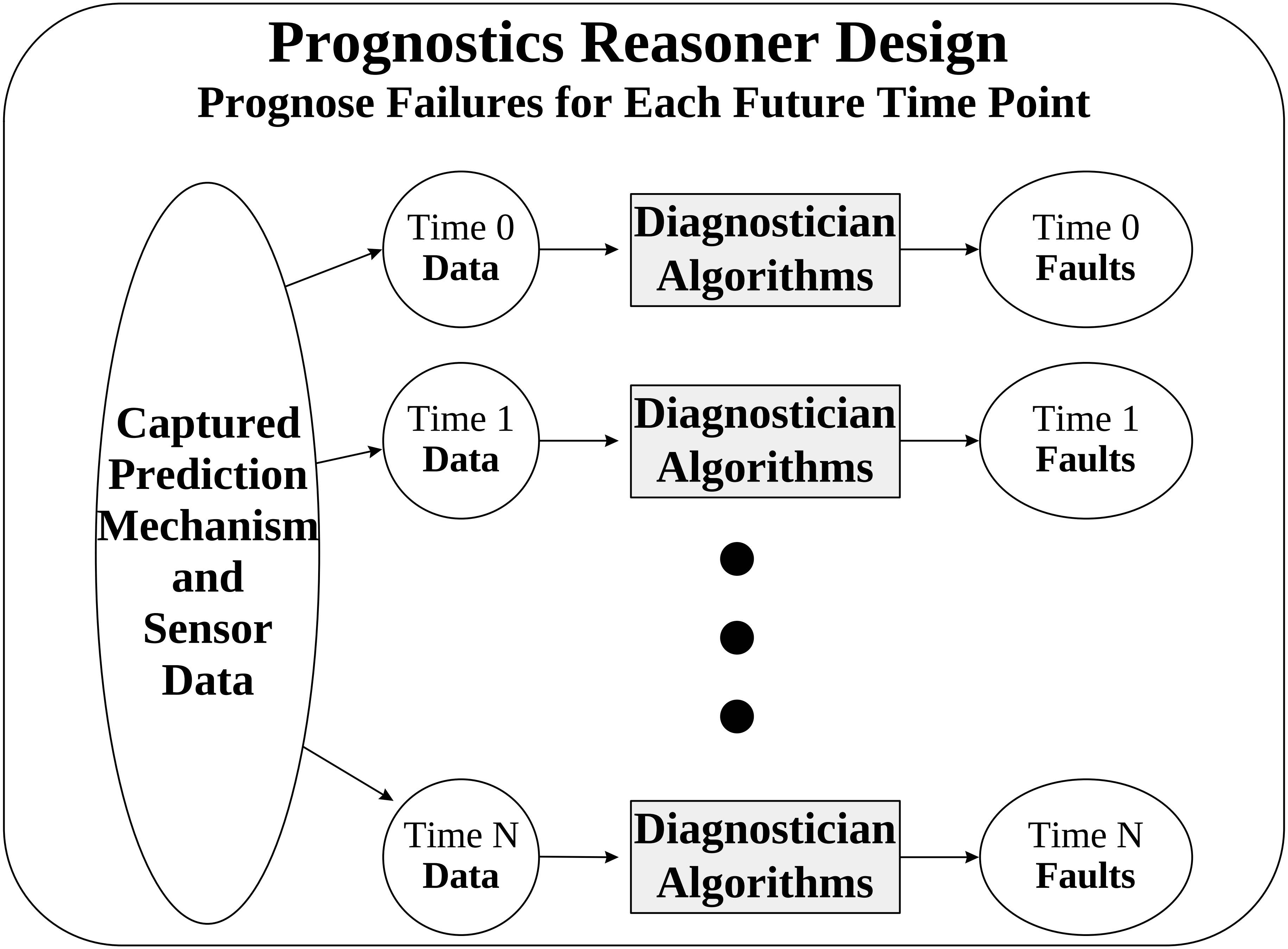
Purpose: Analyze the test and prediction inputs and provide results that are understandable from the mission and maintenance point of view whenever those results are needed

Design Goals: Provide software that (1) can be embedded on a weapons platform, (2) can be tailored using the Prognostics Profiler, and (3) acquires, analyzes, and interprets input data for the use of maintainers, operators, and mission planners

Approach: Provide algorithms based on a three dimensional fault-symptom-time matrix and other tables to acquire data, analyze the results, and generate outputs

Prognostics Reasoner Block Diagram




Prognostics Reasoner Design
Prognose Failures for Each Future Time Point
Captured Prediction Mechanism and Sensor Data
Time 0 Data
Diagnostician Algorithms
Time 0 Faults
Time 1 Data
Diagnostician Algorithms
Time 1 Faults
Time N Data
Diagnostician Algorithms
Time N Faults

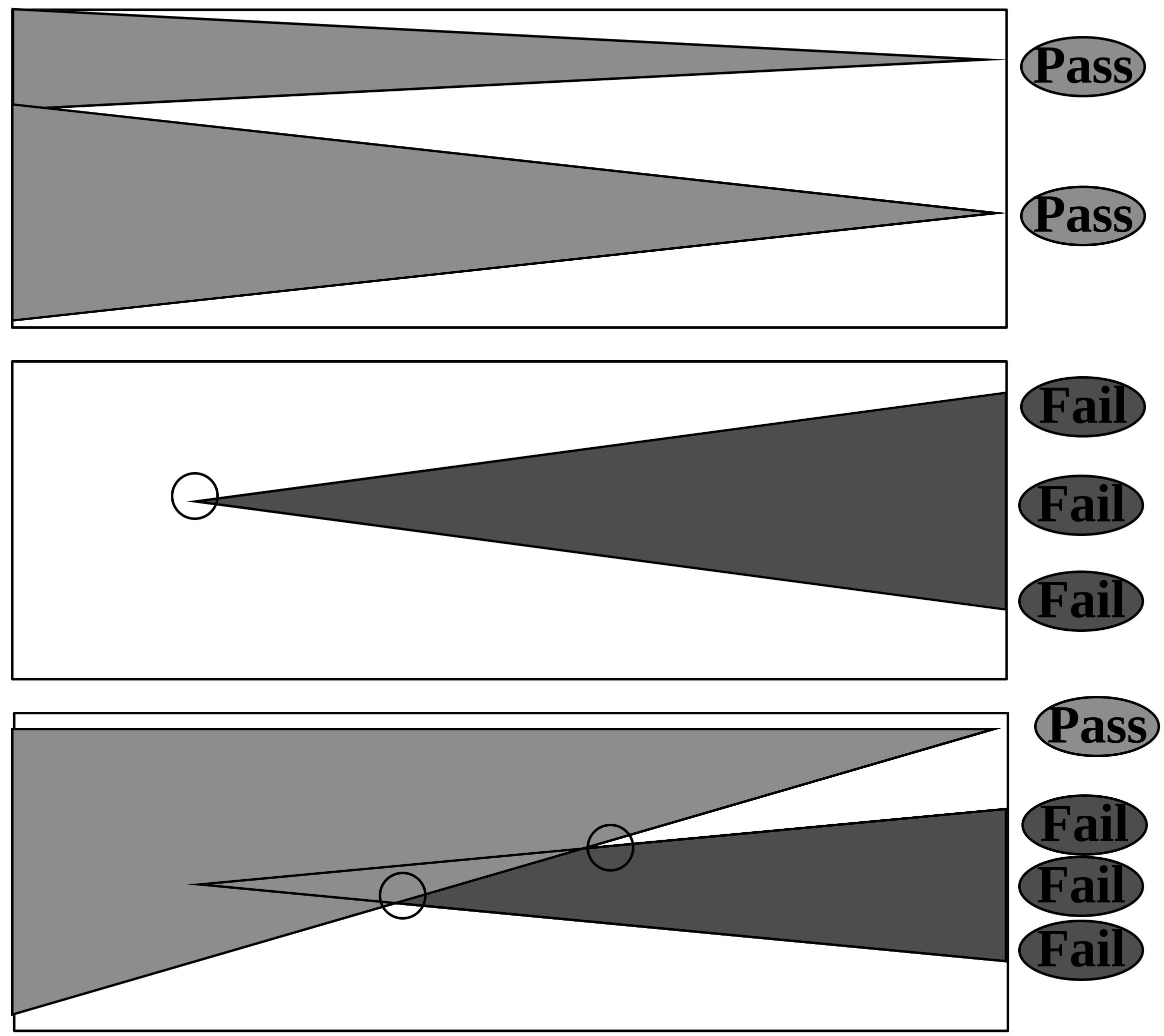
Prognostics Reasoner Design

Diagnostician Algorithms - Cones of Evidence

Pass Data Clears Some Faults

Failure Data Is Explained By Faults

Pass & Fail Data May Identify Multiple Faults



Prognostics Mechanisms Survey Results

Prognostics Framework

Research & Development Efforts

- <u>**Machines and Systems**</u>**: Tanks, rotorcrafts, Navy ships, process and power plants, Joint Strike Fighter, obstacle guidance, etc.**
- <u>**Development works**</u>**: Sensors, Health and Usage Monitoring, Condition Based Maintenance (CBM), Mission Readiness, obstacle Guidance Systems**
- <u>**Types of Prognostics**</u>**: Turbine engines, rotor stability, system vibrations, gears, shafts, power plants, wind tunnel compressors, etc.**

Prognostics Framework

Current Major R&D Efforts

- ❒ **Turbine Engines: PNNL; ARL (D)**
- ❒ **Helicopter gearbox prognostics: Princeton and Boeing/Office of Naval Research (ONR) (E)**
- ❒ **CBM for Intelligent Ship: Pen State/ONR (D)**
- ❒ **Obstacle avoidance: Univ. Southampton & UK Dept. of Defense (R/E)**
- ❒ **Power plants Intelligent Data Acquisition & CBM: PAC & PROSIG (U)**
- ❒ **Wind tunnel compressors automated reasoning expert system: AMES Research Center (D)**
- ❒ **Power transmission systems (MURI IPD): Penn State/ONR (R)**
- ❒ **Statistical Network Modeling (ModelQuest): AbTech/Rome Labs (U)**

PROGNOSTICS FRAMEWORK *DELIVERABLES*

- ❑ Generic Model Structure for Predictive Analysis
- ❑ Prognostics Framework Development Tool and Implementation Guide
- ❑
- ❑ Prototype Prognostics Framework on a Testbed subsystem

IEEE INFORMATION MODEL STANDARDS FOR TEST AND DIAGNOSIS

John Sheppard
ARINC
2551 Riva Road
Annapolis, MD 21401
410-266-2099
jsheppar@arinc.com

Mark Kaufman
NWAS
PO Box 5000
Corona, CA 91718
909-273-5725
kaufman.mark@corona.navy.mil

Abstract *- In this paper we discuss the use of information modeling to develop information exchange standards and metrics for test and diagnostics. For example, fault information is being transferred from one diagnostic reasoner to another. How many attributes does a fault have? One, three, fifteen? How do these attributes relate to the fault, to diagnosis, and tests? If both reasoners do not understand the "model" of a fault, then there will not be an information exchange. Humans can, when they are aware of the differences, resolve the mismatch in information. Computer programs cannot "talk" until they resolve small differences in conceptual information. We present an overview of the current and future directions of the Artificial Intelligence Exchange and Service Tie to All Test Environments (AI-ESTATE) standards. We present a summary of the work completed so far on the diagnostic reasoner exchange standard and on the testability metrics standard.*

We address objectives, document organization, information modeling, service versus API specification, and other issues raised by the AI-ESTATE community. We also discuss the vision of the AI-ESTATE subcommittee in its work to integrate the AI-ESTATE information models and projects such as testability/diagnosability assessment and test/maintenance feedback.

INTRODUCTION

The Artificial Intelligence Exchange and Service Tie to All Test Environments (AI-ESTATE) standards are information exchange standards for test and diagnosis. The original standards, the 1232 series, developed a means of exchange of information between diagnostic reasoners. As the information models for the 1232 standards were developed, it became apparent that these models could be used for standardizing testability and diagnosability metrics. This paper will be discussing the test and diagnosis information exchange standards followed by the testability and diagnosability standards. Other applications of these models will be briefly described.

In 1998, the third of a series of three standards was published by the IEEE addressing issues in system-level diagnostics. IEEE Std 1232-1995 defines the architecture of an AI-ESTATE-conformant system and has been published as a "full-use" standard; however, this standard was published before the vision of AI-ESTATE was fully developed. IEEE Std 1232.1-1997 defines a knowledge and data exchange standard and was published as a "trial-use" standard. Trial-use indicates that it is preliminary in nature, and the standards committee is seeking comments from organizations attempting to implement or use the standard. In 1998, IEEE Std 1232.2-1998 was approved. Its publication, also as a "trial-use" standard is imminent. This standard formally defines a set of standard software services to be provided by a diagnostic reasoner in an open-architecture test environment. Since it is also a trial-use standard, comment and feedback are necessary here as well. The standards were developed using information modeling, resulting in the definition of four information models addressing static and dynamic aspects of the diagnostic domain. Further, the IEEE 1232 AI-ESTATE series of standards provide the foundation for precise and unambiguous testability and diagnosability metrics.

As systems became more complex, costly, and difficult to diagnose and repair, initiatives were started to address these problems. The objective of one of these initiatives, testability, was to make systems easier to test. Early

on, this focused on having enough test points in the right places. As systems evolved, it was recognized that the system design had to include characteristics to make the system easier to test. This was the start of considering testability as a design characteristic. As defined in MIL-STD-2165, testability is "a *design characteristic* which allows the status (operable, inoperable, or degraded) of an item to be determined and the isolation of faults within the item to be performed in a timely manner." [1]. The purpose of MIL-STD-2165 was to provide uniform procedures and methods to control planning, implementation, and verification of testability during the system acquisition process by the Department of Defense (DoD). It was to be applied during all phases of system development—from concept to production to fielding. This standard, though deficient in some areas, provided useful guidance to government suppliers. Further, lacking any equivalent industry standard, many commercial system developers have used it to guide their activities although it was not imposed as a requirement.

In this paper, we present an overview of the current and future directions of the AI-ESTATE standards. We address objectives, document organization, information modeling, service versus Applications Program Interface (API) specification, and other issues raised by the AI-ESTATE community. We also discuss the vision of the AI-ESTATE subcommittee in its work to integrate the AI-ESTATE information models and projects such as testability/diagnosability assessment and test/ maintenance feedback.

A VISION FOR TEST AND DIAGNOSIS STANDARDS

Diagnosis

The vision of AI-ESTATE is to provide an integrated, formal view of diagnostic information as it exists in diagnostic knowledge bases and as it is used (or generated) in diagnostic systems. We assert that the whole purpose of testing is to perform diagnosis [2]. In justifying this assumption, we rely on a very general definition of diagnosis, derived from its Greek components (δια γιγνωσκω) meaning, "to discern apart." Given such a broad definition, all testing is done to provide information about the object being tested and to differentiate some state of that object from a set of possible states.

In support of this vision, the AI-ESTATE committee has been working on combining the existing standards into a single, cohesive standard. This "unified" standard provides formal specifications of all of the information models (both for file exchange and for diagnostic processing), from which the service specifications are then derived and specified. The architectural framework is retained at the conceptual level to emphasize that a wide variety of implementation models are possible that still support standard exchange of information as long as the definition of that information is clear and unambiguous. Thus, in a sense, the models define the architecture, and the implementation is left entirely to the implementer.

With this vision in mind, we believe AI-ESTATE plays a central role in any test environment (thus the "All Test Environments" part of the name). To date, the focus of the standards has been the development of specifications supporting diagnosis in the traditional sense of the word (i.e., fault isolation). However, the broader context within which AI-ESTATE is envisioned to participate involves tying diagnostic information to explicit product behavior descriptions, assessments of the ability of testing to satisfy its requirements, and maturation of the diagnostic process through test and maintenance information feedback.

Testability

In 1997, the AI-ESTATE committee began to work on a new standard focusing on replacing the cancelled MIL-STD 2165. The military standard focused on specifying the essential elements of a testability program and explained the elements needed to define a testability program plan. In addition, MIL-STD 2165 included the "definition" of several testability metrics, including a testability checklist to be used to determine overall system testability. With the cancellation of military standards and specifications by the Perry Memo in 1994 [3], and with the lack of specificity and clarity in MIL-STD 2165, it became evident that a replacement was necessary.

The approach being taken to develop this standard involves defining testability and diagnosability metrics based on standard information models. Specifically, it was found that the AI-ESTATE models provided an excellent foundation for defining these metrics

THE AI-ESTATE ARCHITECTURE

According to IEEE Std 1232-1995, the AI-ESTATE architecture is "a conceptual model" in which "AI-ESTATE applications may use any combination of components and intercomponent communication" [4]. On the other hand, according to IEEE Std 1232.2-1998, AI-ESTATE includes explicit definitions of services to be provided by a diagnostic reasoner, where the services "can be thought of as responses to client requests from the other components of the system architecture" [5]. More specifically, "each of the elements that interface with the reasoner will interact through [an] application executive and will provide its own set of encapsulated services to its respective clients" [5].

Although not necessarily obvious from the standards themselves, these two "views" of the AI-ESTATE architecture present an interesting dichotomy. Specifically, the architecture standard provides a concept of AI-ESTATE that permits any communication mechanism to be used between components of a test environment in support of the diagnostics provided by that environment. The service specification, on the other hand, seems to cast the communication mechanism in the form of a client-server architecture.

We note that the intent of AI-ESTATE is to provide a formal, standard framework for the exchange of diagnostic information (both static and dynamic) in a test environment. This exchange occurs at two levels. At the first level, data and knowledge are exchanged through a neutral exchange format, as specified by IEEE Std 1232.1-1997 [6]. At the second level, specified by IEEE Std 1232.2-1998 [5]information is exchanged as needed between software applications within the test environment. This information includes entities from a model or information on the current state of the diagnostic process.

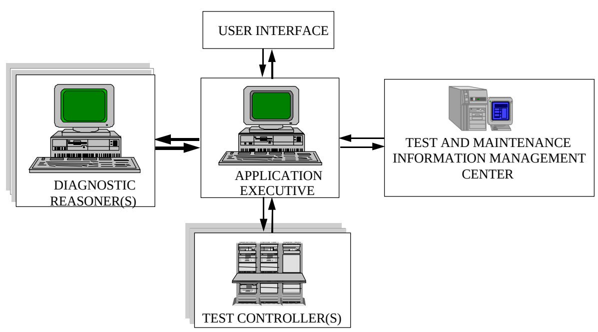


Figure 1. AI-ESTATE Architecture

To facilitate encapsulation of the information and the underlying mechanisms providing that encapsulation, AI-ESTATE assumes the presence of an "application executive." We emphasize that this application executive need not be a physically separate software process but can be identified as a "view" of the software process when it involves the communication activity. This view of the architecture is shown in Figure 1. In the following sections, we will provide a more detailed discussion of the exchange and service elements of the architecture.

Data and Knowledge Exchange

ISO 10303–11 (EXPRESS) and ISO 10303–12 (EXPRESS-I) are used to define information models and exchange formats for diagnostic knowledge [7], [8]. These international standards are being maintained by the STEP (Standard for the Exchange of Product model data) community. The current approach to static information exchange within AI-ESTATE is to derive the exchange format from the formal information models as specified in the ISO standards.

The purpose of information modeling is to provide a formal specification of the *semantics* of information that is being used in an "information system." Specifically, information models identify the key entities of information to be used, their relationships to one another, and the "behavior" of these entities in terms of constraints on valid values [9]. The intent is to ensure that definitions of these entities are unambiguous.

For example, central to the test and diagnosis problem is the definition of a "test." If we ask a digital test engineer what a test is, it is possible that the answer will be something like "a set of vectors used to determine whether or not a digital circuit is working properly." On the other hand, if we ask a diagnostic modeler what a test is, the answer is likely to be "any combination of stimulus, response, and a basis for comparison that can be used to detect a fault."

On the surface, these two definitions appear very similar; however, there is a fundamental difference. For the digital test engineer, there is an implicit assumption that a "test" corresponds to the entire suite of vectors. For the diagnostic modeler, individual vectors are tests as well.

As a similar example, the test engineer and diagnostic modeler are likely to have different definitions for "diagnosis." The act of doing diagnosis, for most test engineers, corresponds to running tests after dropping off of the "go-path." For the diagnostic modeler, since "no fault" is a diagnosis, the entire test process (including the go-path) is part of doing diagnosis.

It may appear that we are "splitting hairs," but formal definition of terms and information entities is an exercise in splitting hairs. Further, such hair-splitting is essential to ensure that communication is unambiguous—especially when we are concerned with communication between software processes. No assumption can go unstated;

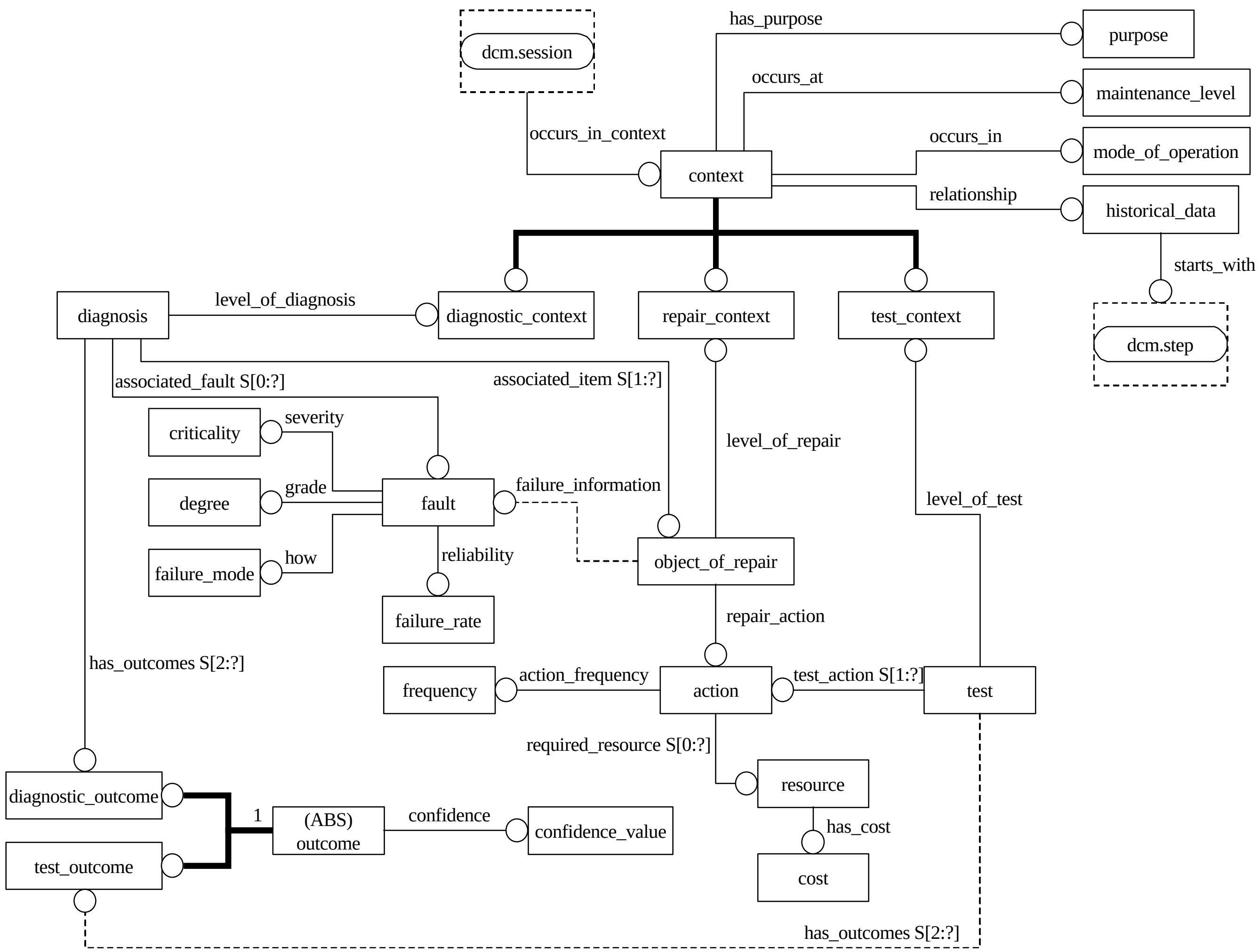


Figure 2. Revised Common Element Model

otherwise, the risk exists that something will be misunderstood. Information models formally state all of the assumptions.

A New Information Model

When IEEE 1232.1 was published, it was published as a "trial-use" standard to provide a period for people to study it, attempt to implement it, and provide feedback to the AI-ESTATE committee on the ability of the standard to satisfy the stated requirements. Since publication, comments have been received to indicate that ambiguity still exists in the information models.

Because of the concern that the information models are still ambiguous, the models are undergoing close examination and modification. It is interesting to note that much of the ambiguity has been identified in connection with a related standard being developed by the AI-ESTATE committee—P1522 Standard for Testability and Diagnosability Metrics and Characteristics. AI-ESTATE's approach to developing this new standard involved defining the metrics based on the information models within the P1232 standard. As we were identifying metrics to be standardized, we discovered that the current models were incapable of supporting their definition.

A conceptual view of the revised common element model is shown in Figure 2. Of note in the revised model is the addition of a context entity and the differentiation between fault and function. Many diagnostic tools are highly context dependent (e.g., different procedures are suggested based on the environmental conditions of the test or the skill levels of the maintenance technicians). In addition, several tools focus on modeling function rather than physical faults to support modeling at the system level. Since the distinctions among context and type of analysis were not previously made explicit, new entities were defined to eliminate ambiguity that may arise from different approaches and contexts for modeling.

Diagnostic Services

The approach taken to defining services in AI-ESTATE has been based on the traversal (i.e., the following of the relationships defined between model entities to access specific pieces of information in the models) of the information models. The "simplest" services involve traversing the models defined in IEEE 1232.1 (i.e., the exchange models); however, these models provide little functionality in terms of actual diagnosis.

In IEEE 1232.2, a novel use of information modeling was applied in that a dynamic information model was specified to support dynamic services. This model, called the "dynamic context model," relied on dynamically creating entities that populate the model during a diagnostic session. In fact, as suggested by "dcm.session" and "dcm.step" in the model shown in Figure 2, a diagnostic session is modeled as a sequence of steps instantiated from the set of possible values specified in the static model. Details of how the service specification is expected to be implemented can be found in [10], [11].

One of the concerns raised by a member of the AI-ESTATE committee was whether the standard specifies a set of services or simply an Application Programming Interface. The claim was that the service specification must include a behavior specification as well and that this can only be accomplished by defining a set of baseline behaviors, perhaps through some sort of test bed.

The committee observed that people have different opinions over the difference between a service specification and an API specification. Many, in fact, took issue with the claim that they were different. Further, it was determined that including test cases to specify standard behavior was not desirable in this context due to the wide variety of diagnostic approaches using common diagnostic knowledge. Rather, it was believed that it was more important for the information itself to be standardized and the specific behavior to be left to the implementation.

Testability and Diagnosability Metrics

Testability has been broadly recognized as the "-ility" that deals with those aspects of a system that allow the status (operable, inoperable, or degraded) or health state to be determined. Early work in the field primarily dealt with the design aspects such as controllability and observability. Almost from the start this was applied to the manufacturing of systems where test was seen as a device to improve production yields. This has been slowly expanded to include the aspects of field maintainability such as false alarms, isolation percentages, and other factors associated with the burden of maintaining a system.

In the industry, many terms such as test coverage and Fraction of Fault Detection (FFD) are not precisely defined or have multiple definitions. Further, each diagnostic tool calculates these terms differently and therefore the results are not directly comparable. Some measures, such as false alarm rate, are not measurable in field applications. Other measures such as Incremental Fault Resolution, Operational Isolation, and Fault Isolation Resolution appear different, but mean nearly the same thing.

Lacking well-defined testability measures, the tasks of establishing testability requirements, and predicting and evaluating the testability of the design are extremely difficult. This in turn makes effective participation in the design for testability process difficult. These difficulties will be greatly diminished by the establishment of standard testability metrics. An immediate benefit will come with a consistent, precise, and measurable set of testability attributes that can be compared across systems, tools, and within iterations of a system's design.

MIL-STD-2165 did not have precise and unambiguous definitions of measurable testability figures-of-merit and relied mostly on a weighting scheme for testability assessment. (It should be noted, however, that the standard did permit the use of analytical tools for testability assessment such as SCOAP, STAMP, and WSTA).

As we strive to establish concurrent engineering practices, the interchange between the testability function and other functions becomes even more important. To create integrated diagnostic environments, where the elements of automatic testing, manual testing, training, maintenance aids, and technical information work in concert with the testability element, we must maximize the reuse of data, information, knowledge, and software. Complete diagnostic systems include Built-In-Test (BIT), Automatic Test Equipment (ATE), and manual troubleshooting. It would be desirable to be able to predict and evaluate the testability of systems at these levels.

It is not an accident that the P1522 standard contains both the word testability and the word diagnosability. The distinction is not always easy to maintain, especially in light of the expansion of the use of the testability term. Figure 3 shows the basic relationship, with diagnosability being the larger term and encompassing all aspects of detection, fault localization, and fault identification. The boundary is fuzzy and often it is not clear when one term applies and the other does not. The P1522 standard is meant to encompass both aspects of the test problem. Because of the long history of the use of the testability term, we will seldom draw a distinction. However, the use of both terms is significant in that testability is not independent of the diagnostic process. The writing of test procedures cannot and should not be done separately from testability analyses. To do so, would be meeting the letter of the requirements without considering the intent.

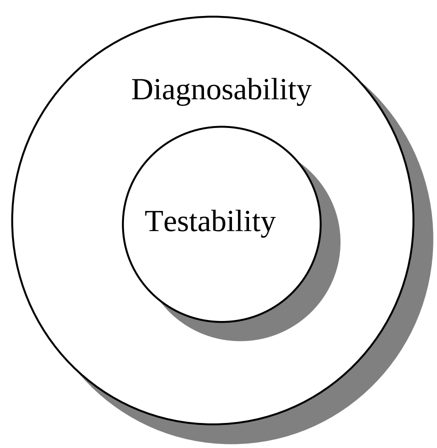


Figure 3. Relationship Between Diagnosability and Testability

TESTABILITY AND DIAGNOSABILITY METRICS OBJECTIVES

It is the objective of the P1522 standard to provide notionally correct, inherently useful, and mathematically precise definitions of testability metrics and characteristics. It is expected that the metrics may be

used to either measure the testability of a system, or predict the testability of a system. Notionally correct means that the measures are not in conflict with intuitive and historical representations. Beyond that, the measures must be either measurable or predictable. The former may be used in the specification and enforcement of acquisition clauses concerning factory and field-testing, and maintainability of complex systems. The latter may be used in an iterative fashion to improve the factory and field-testing and maintainability of complex systems. The most useful of all are measures that can be used for both. Because of the last point, the emphasis will be on measurable quantities (metrics).

Things that can be enumerated by observation and folded into the defined figures-of-merit will be developed into metrics. However, a few measures are inherently useful on the design side even if they are not measurable in the field and they are defined in a separate section in P1522. The end purpose is to provide an unambiguous source for definitions of common and uncommon testability and diagnosability terms such that each individual encountering the metric can know precisely what that metric measures.

ISSUES

MIL-STD-2165 defined Fraction of Faults Detected (FFD) two ways. The first is the fraction of *all* faults detected by BIT/External Test Equipment (ETE). The second is the fraction of *all detectable* faults detected by BIT/ETE [1]. False alarms were excluded from the definition. From these two variations grew many others. As noted in "Organizational-Level Testability" [12] FFD can be defined as:

- Fraction of all faults detected or detectable by BIT/ETE
- Fraction of all detectable faults detected or detectable with BIT/ETE
- Fraction of all faults detected through the use of defined means. Defined means implies all means of detection that have been identified.
- Percentage of all faults automatically detected by BIT/ETE
- Percentage of all faults detectable by BIT/ETE
- Percentage of all faults detectable on-line by BIT/ETE
- Percentage of all faults and out-of-tolerance conditions detectable by BIT/ETE
- Percentage of all faults detectable by any means

One problem with traditional metrics is that they are "overloaded." Overloaded in this case means that due to "common understanding" of the terms, fine variations are not specified. Consequently, users of the term do not necessarily know the implications of a precise definition. Discussions of overloaded terms go on at length, in part because everyone in the discussion has brought along a lot of mental baggage. Often, progress is only made when a neutral term is chosen and the meaning is built from the ground up. This overloading is so severe, for example, that there was no definition of FFD in *System Test and Diagnosis* [2], the authors preferring to use Non-Detection Percentage (NDP). FFD is the negative of NDP and is equal to 1–NDP.

Even the number of faults counted in the field require a more precise definition. The "overloaded" version is simply a count of all the things that failed. The quantity of all faults, as usually defined in the industry, is different. The quantity of faults detected by BIT/ETE, and the quantity of faults detected exclude the occurrence of false alarms. Intermittent faults are classified as a single fault. Temporary faults, those caused by external transients of noise, are not classified as faults.

```
FUNCTION ffd(model:EDIM.edim; lvl:CEM.level) : REAL;
      LOCAL
            diag_count : INTEGER;
            diags : SET [0:?] OF EDIM.inference
            detect_set : SET [0:?] OF CEM.diagnosis := NULL;
      END_LOCAL;

      diag_count := SIZEOF(QUERY(tmp <* model.model_diagnosis |
      tmp.level_of_diagnosis = lvl);
      REPEAT I := LOINDEX(model.inference) TO HIINDEX(model.inference);
            diags := QUERY(tmp <* model.inference[I].conjuncts |
                        (TYPEOF(tmp) = 'EDIM.diagnostic_inference'));
            diags := diags + QUERY(tmp <* model.inference[i].disjuncts |
            IEEE Std 1232.1-1997diags := QUERY(tmp <* diags |
                        tmp.pos_neg = negative OR
                        NOT(tmp.diagnostic_assertion = 'Good'));
            detect_set := detect_set + QUERY(tmp <* diags.for_diagnosis |
                        tmp.level_of_diagnosis = lvl);
      END_REPEAT;
      RETURN(SIZEOF(detect_set) / diag_count);


END_FUNCTION;
```

Figure 4. Sample Metric Definition in EXPRESS

Another aspect of the challenge is that many metrics sound different but are not. Below are some examples.

- *Ambiguity Group Isolation Probabilities* is the cumulative probability that any detected fault can be isolated by BIT or ETE to an ambiguity group of size L or less.

- *Fault Isolation Resolution* is the cumulative probability that any detected fault can be isolated to an ambiguity group of a targeted size or less.

- *Isolation Level* is the ratio of the number of ambiguity groups to the total number of isolatable components.

- *System Operational Isolation Level* is the percentage of observed faults that result in isolation to *n* or fewer replaceable units.

All of these terms were and are valuable. The value of these terms will be increased with precise meanings for each one.

ASSUMPTIONS

The development of a diagnostic capability includes system level analysis. As such, it is assumed that a system level approach is undertaken, and those diagnostic strategies and testability criteria have been explicitly developed or at least structured. These may be variables in the formulation, but cannot be completely undefined. The primary assumptions are twofold and deal with inherent usefulness from prior experience and the ability to precisely define the term from first principles. In some cases, we will assume the existence of a diagnostic model such as one based on the IEEE 1232 series of standards. Metrics will be derived from the entities and attributes based on these information models. In other cases, we will rely on a demonstrated ability to measure items related to the testing at the design, factory, and field levels concerning the maintainability of complex systems. In the latter case, information models will be developed as necessary to define all relevant entities and attributes.

Each term carries with it a number of additional assumptions (such as single or multiple failure) and is explicitly dealt with on a term by term basis in the section on metrics and characteristics.

The FFD metric assumes the existence of a diagnostic model that ties tests (especially test outcomes) to potential faults in the system analyzed. Within AI-ESTATE, tests, diagnoses, and faults are modeled explicitly in the common element model. In addition, AI-ESTATE includes specifications for two diagnostic models—the fault tree model and the Enhanced Diagnostic Inference Model (EDIM). Due to its generality, the EDIM was used to define FFD.

The assumptions used to define FFD are as follows:

- We are interested in the various metrics at a particular level;
- A hierarchical element exists at a particular level;
- No descendant of a hierarchical element is at the same level as that hierarchical element; and
- At this point, we don't care about the ordering of the levels.

As an example, one metric defined using the model is Fractions of Faults Detected (FFD).

From these assumptions and the information models, we can define FFD using the procedural constructs of EXPRESS. Specifically, a function (FFD) can be specified as in Figure 4. In the process of defining this one metric, several issues were identified. These issues are discussed in detail in [13].

OTHER APPLICATIONS

Ties to Maintenance Feedback

In 1993, a Project Authorization Request (PAR) was submitted to the IEEE for new standards project related to specifying information and services for test and maintenance information feedback. The Test and Maintenance Information Management Standard (TMIMS) project was approved by the IEEE in early 1994. The focus of this project was to define exchange and service standards (similar to AI-ESTATE) which support the test and diagnostic maturation process. In 1998, due to a lack of progress, the TMIMS PAR was cancelled.

AI-ESTATE continues to require definition of exchange and service standards related to test and maintenance information. In 1998, shortly after the cancellation of the TMIMS PAR, the AI-ESTATE committee decided to include test and maintenance information in its scope. The approach will be consistent with AI-ESTATE (i.e., the definition of information models and EXPRESS-level services derived from traversing the models). Further, it is anticipated that the starting point for the new models will be the dynamic context model in IEEE 1232.2. By keeping track of the sequence of events during a diagnostic session, much of the historical information is identified and captured that can be used for later diagnostic maturation.

Ties to Product Descriptions

Through the 1990s, the IEEE has been developing a family of standards under the umbrella of “A Broad Based Environment for Test” (ABBET) [14], [15]. An early architecture of ABBET, based on information modeling, presented ABBET as five layers: 1) product description, 2) test requirements/strategy, 3) test methods, 4) test resources, and 5) instrumentation. Since then, standards for the “lower layers” of ABBET (i.e., layers 3–5) have been defined; however, it has long been recognized that the major benefit from standardization will come from the “upper layers” (i.e., layers 1 and 2).

AI-ESTATE satisfies many of the requirements related to layer two of ABBET (however, AI-ESTATE has never been considered part of the ABBET family). Further, a recent proposal for a new information model-based standard, called the Test Requirements Model (TeRM), will address specific concerns of test requirements [16], [17]. Standards for the product description layer have always been problematic due to issues related to the revelation of intellectual property. With the combination of TeRM, AI-ESTATE, and TMIMS, it is anticipated that intellectual property can be hidden from information provided in standard form while still supporting the test engineer fully.

CONCLUSION

Reasoning system technology has progressed to the point where electronic and other complex systems are employing artificial intelligence as a primary component in meeting system test and verification requirements. This is giving rise to a proliferation of AI-based design, test, and diagnostic tools. Unfortunately, the lack of standard interfaces between these reasoning systems has increased the likelihood of significantly higher product life-cycle cost. Such costs arise from redundant engineering efforts during design and test phases, sizeable investment in special-purpose tools, and loss of system configuration control.

The AI-ESTATE standards promise to facilitate ease in production testing and long-term support of systems, as well as reducing overall product life-cycle cost. This will be accomplished by facilitating portability, knowledge reuse, and sharing of test and diagnostic information among embedded, automatic, and stand-alone test systems within the broader scope of product design, manufacture, and support.

AI-ESTATE was first conceived in 1988 as a standard for representing expert-system rule bases in the context of maintenance data collection. Since that time, AI-ESTATE has evolved to be embodied in three published standards related to the exchange of diagnostic information and the interaction of diagnostic reasoners within a test environment. The three standards have been recommended for inclusion on the US DoD ATS Executive Agent’s list of standard satisfying requirements for ATS critical interfaces. In looking to the next generation, AI-ESTATE is expanding to address issues of testability, diagnosability, maintenance data collection, and test requirements specification.

ACKNOWLEDGMENTS

In many ways, it is unfortunate that a paper such as this includes only the names of two authors. The work reported here is the result of efforts of a committee of devoted volunteers who have supplied their expertise in system test and diagnosis to develop strong, sound standards supporting the diagnostics community. We would like to thank Les Orlidge, Randy Simpson, Tim Bearse, Tim Wilmering, Greg Bowman, Dave Kleinman, Lee

Shombert, Sharon Goodall, Len Haynes, Jack Taylor, and Helmut Scheibenzuber for their efforts in developing the standards and promoting their use in industry.

REFERENCES

[1] MIL STD 2165. 1985. *Testability Program for Electronic Systems and Equipment*, Washington, DC: Naval Electronic Systems Command (ELEX-8111

[2] Simpson, W. and Sheppard, J. 1994. *System Test and Diagnosis*, Boston, MA: Kluwer Academic Publishers.

[3] Perry, William. 1994. "Specifications and Standards—A New Way of Doing Business," US Department of Defense Policy Memorandum.

[4] IEEE Std 1232-1995. *IEEE Standard for Artificial Intelligence Exchange and Service Tie to All Test Environments (AI-ESTATE): Overview and Architecture*, Piscataway, NJ: IEEE Standards Press.

[5] IEEE Std 1232.2-1998. *IEEE Trial-Use Standard for Artificial Intelligence Exchange and Service Tie to All Test Environments (AI-ESTATE): Service Specification*, Piscataway, NJ: IEEE Standards Press.

[6] IEEE Std 1232.1-1997. *IEEE Trial-Use Standard for Artificial Intelligence Exchange and Service Tie to All Test Environments (AI-ESTATE): Data and Knowledge Specification*, Piscataway, NJ: IEEE Standards Press.

[7] ISO 10303-11:1994. *Industrial Automation Systems and Integration—Product Data Representation and Exchange—Part 11: Description Methods: The EXPRESS Language Reference Manual*, Geneva, Switzerland: International Organization for Standardization.

[8] ISO 10303-12:1997. *Industrial Automation Systems and Integration—Product Data Representation and Exchange—Part 12: Description Methods: The EXPRESS-I Language Reference Manual*, Geneva, Switzerland: International Organization for Standardization.

[9] Schenk, D. and Wilson, P. 1994. *Information Modeling: The EXPRESS Way*, New York: Oxford University Press.

[10] Sheppard, J. and Maguire, R. 1996. "Application Scenarios for AI-ESTATE Services," *AUTOTESTCON '96 Conference Record*, New York: IEEE Press.

[11] Sheppard, J. and Orlidge, L. 1997. Artificial Intelligence Exchange and Service Tie to All Test Environments (AI-ESTATE)—A New Standard for System Diagnostics," *Proceedings of the International Test Conference*, Los Alamitos, CA: IEEE Computer Society Press.

[12] Simpson, W., Bailey, J., Barto, K. and Esker, E., 1985 "Organization-Level Testability Prediction", ARINC Research Corporation Report 1511-01-3623 Prepared for the Rome Air Development Center.

[13] Kaufman, M. and Sheppard, J. 1999. "IEEE P1522—A Formal Standard in Testability and Diagnosability Assessment, *AUTOTESTCON '99 Conference Record*, New York: IEEE Press.

[14] IEEE Std 1226-1993. *IEEE Trial-Use Standard for A Broad Based Environment for Test (ABBET): Overview and Architecture*, Piscataway, NJ: IEEE Standards Press.

[15] IEEE Std 1226.6-1996. *IEEE Guide to the Understanding of A Broad Based Environment for Test (ABBET)*, Piscataway, NJ: IEEE Standards Press.

[16] Shombert, L. 1998. *Test Requirements Model Language Reference Manual*, Draft 0.1, Technical Report CAE-1998-07-01, Vienna, VA: Intermetrics.

[17] Shombert, L. and Sheppard, J. 1998. "A Behavior Model for Next Generation Test Systems," *Journal of Electronic Testing: Theory and Applications*, Vol. 13, No. 3.

Automatic Detection of Radar Signature Defects

Nancy Cheadle, Naval Air Warfare Center,
Dennis Tackett, Modern Technology Solutions, Inc.,
Robert Pierce, Naval Surface Warfare Center and
Raymond de Lacaze, Knowledge Technologies International

Abstract

Field-level maintenance of radar signature treatment requires that non-specialist military personnel properly identify needed repairs. To simplify this task, an automated method is required that can compare radar signature data to baseline data, measure the differences, and identify the source of serious defects. Significant work has been done using artificial intelligence (AI) techniques to simplify this diagnostic task. A portable measurement radar was used to gather signature data on a small MQM-107D target drone. One set of data was collected of a baseline vehicle. Then data was collected after several anomalies were introduced, such as an uncovered pitot tube, wing joint untaped, or fastener screw not tightened. The data was processed as global downrange plots, and then baseline data was subtracted from anomaly data and the difference was compared to signature specifications as a function of angle. AI was used to identify signature defects that require repair. The results showed that an AI-aided diagnostic tool could help identify places where signature treatment repair was needed. This tool can be adapted to a variety of user and target needs.

Introduction

Low Observable (LO) systems require specialized measurement equipment to ensure the LO characteristics are sustained. A portable diagnostic measurement system to assist maintainers of LO aircraft is required to provide measurement capability to meet the In-Service radar cross section (RCS) measurement framework, assess mission readiness and capability, and provide near real-time results. Defect isolation, diagnosis and RCS assessment are important attributes of the signature maintenance function. The purpose of this effort, managed by the Advanced Technology Test Team (ATTT), was to develop a system, which could measure an item and determine the signature health of that item with minimal human interaction. The desired features include a single system with organic measurement and analysis capability, a system that is adaptive to various users and LO assessment needs, and the ability to use a variety of methods to determine corrective actions. This paper provides the details of the development of automatic anomaly detection software.

ICON Downrange Profile System

The Icon Downrange Profile system is an anomaly detection and registration program based on the analysis of downrange profiles. The software provides graphical facilities for loading reference and target data, finding differences between the latter, building data abstractions of these differences and automatically matching the differences with known anomalies. Users can also register newly encountered differences. The system allows graphical retrieval and comparison of registered anomalies. The differencing and matching phases of the analysis are complex processes that use clustering algorithms to create abstract representations of the differences (known as *clusters*) which can be registered into an anomaly database. Menus are provided to allow users to fine-tune the various processing parameters in each of the phases of the analysis. The

clustering techniques were very successful in recognizing differences and providing the necessary data abstraction paradigms for correctly retrieving known anomalies from the database and distinguishing between them. The Icon system exploits Knowledge Technologies' *GBB™* and *ChalkBox™* products.

Figure 1 outlines the phases involved in data analysis. The end result is either a match with a known anomaly(s) or the option to register a newly detected type of anomaly. There are three major phases: the image analysis phase, the cluster analysis phase and the anomaly detection/registration phase. Each of these phases takes place at a different level of abstraction.

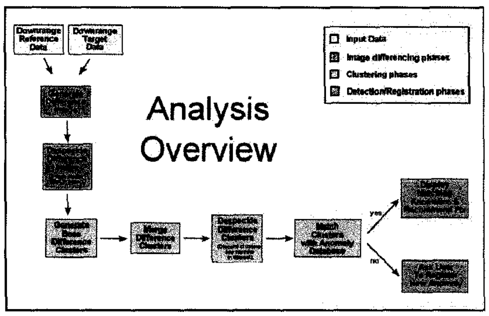


Figure 1. Analysis Overview.

Each of these steps has proven crucial to the overall process. The image analysis phases provide data alignment and noise elimination. The clustering phases provide not only data abstraction, but also a significant amount of data compression. The anomaly detection phases rely on advanced matching facilities.

The Icon analysis phases comprise three levels of data abstraction. These are the *data-point level*, the *cluster level* and the *anomaly (composite cluster) level.* Figure 2 outlines the three semantic levels and indicates which analysis activities are performed at each. Notice for example that there is a despeckling phase at both the data-point level and the cluster level of the overall analysis.

At the data-point level, operations are performed on individual points in the downrange profile. At the cluster level, groups of data points (*clusters*) are created and operations are performed on individual clusters. Finally at the anomaly level, groups of *clusters (set-composite clusters)* are created as composite objects. At this level, operations are performed on groups of clusters.

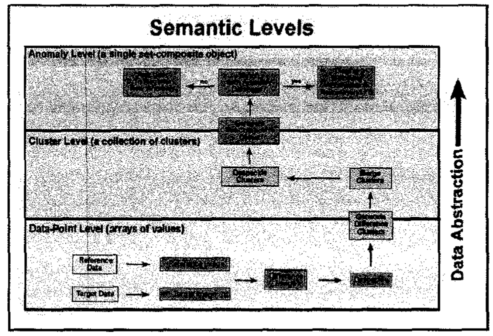


Figure 2. Data Abstraction Levels.

Example/Software Validation

To validate the usefulness of the software, measurements were taken on the MQM-107 target drone. Measurements were taken in a "pristine" condition and then realistic defects were implanted on the vehicle. The MQM-107 is shown in Figure 3. As an example of the detection process the port access screws were not secured as shown in Figure 4.

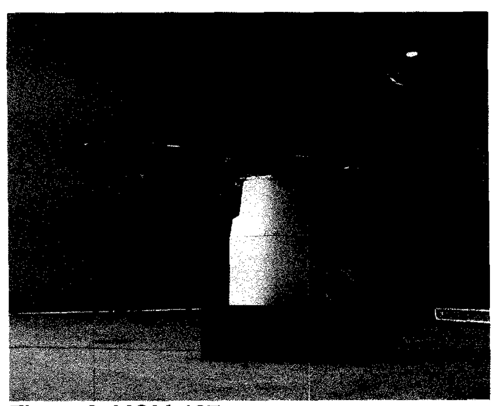


Figure 3. MQM-107

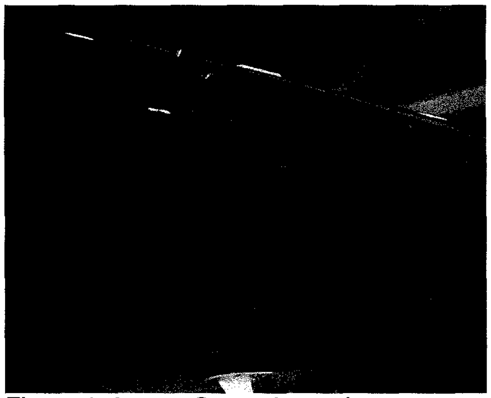


Figure 4. Access Screw Anomaly

Figure 5 presents the output of the anomaly detection process. As can been seen, in the difference data frame, the software successfully found the anomaly.

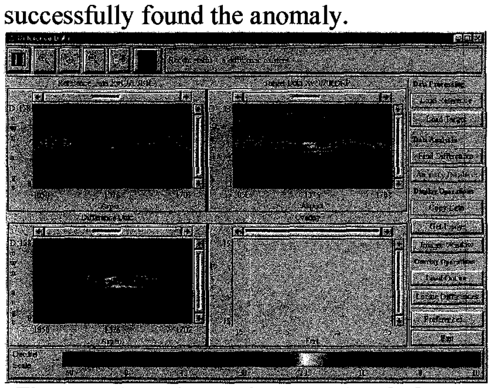


Figure 5. Icon Anomaly Detection Software Output.

Summary

This initial effort of developing automatic detection of radar signature defects was very successful. Distinguishable differences have been detected and clusters generated coincided with perceived regions of differences in the target data. Future efforts will include development of a more extensive anomaly database, extending and optimizing the clustering techniques, adapting the Icon software to ISAR data, and automating the parameter selection process.

Sponsoring Agency Acknowledgment

This effort was sponsored by the Office of Naval Research and managed by Advanced Technology Test Team (ATTT).

Automatic Detection of Radar Signature Defects

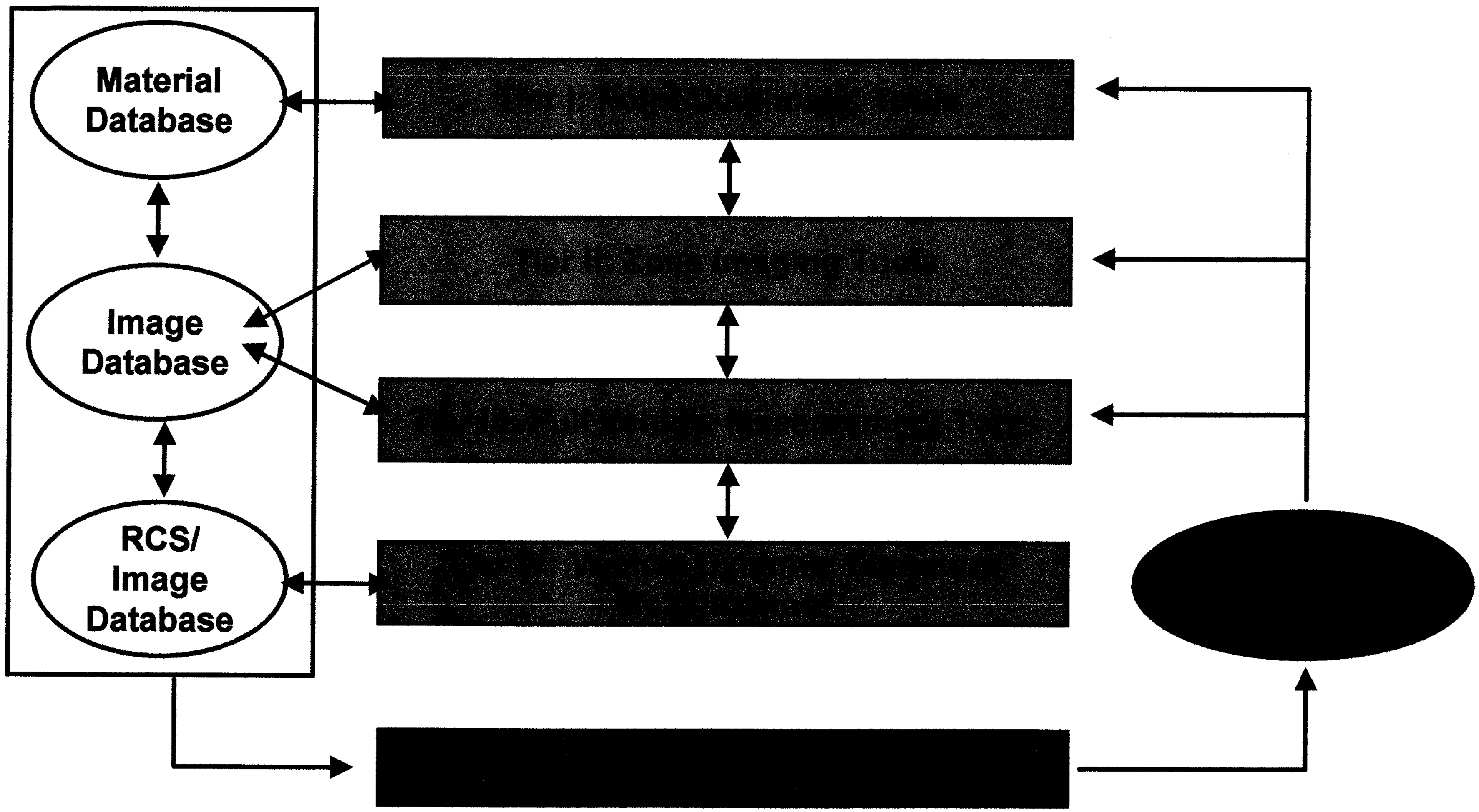
Nancy Cheadle
Naval Air Warfare Center/Weapons Division
Code 472210d
China Lake, CA

Requirement for Portable Measurement System

- **Problem:** LO systems must be monitored to ensure LO characteristics are maintained

- **Proposed Solution:** Portable diagnostic measurement system to assist maintainers of LO aircraft
  - Provides measurement capability for Tier II and Tier III of the In-Service RCS measurement framework
  - Assesses mission readiness and capability
  - Provides near real-time results

In-Service RCS Measurement Framework



Different Needs

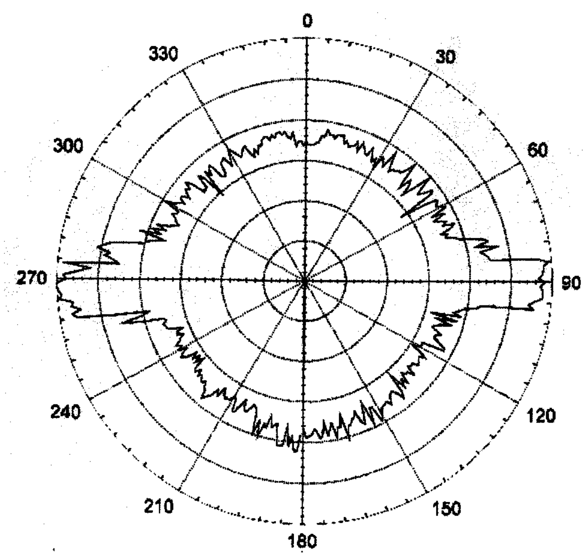
RCS Measurement System Users

	LO Development Engineers	LO Maintenance Personnel
Frequencies	**Many**	**Few**
Time Available	**Almost Enough**	**Very Little**
Environment	**Controlled**	**Semi-prepared**
Experience	**Detailed**	**General**
Cost	**Important**	**Critical**

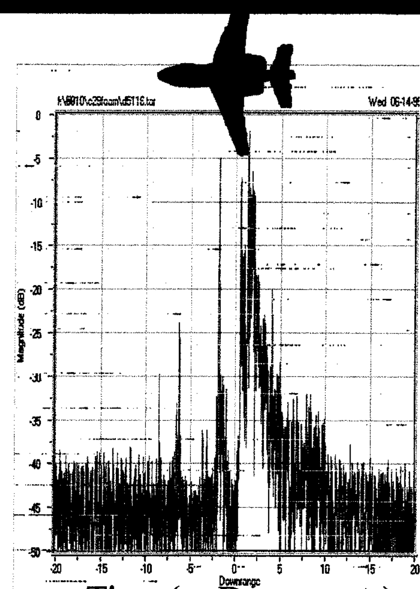
Signature Maintenance Functions

- Vehicle RCS verification
  - Confirm vehicle signature is at or below fleet signature threshold
- Defect isolation
  - Determine location of defects causing degradation of vehicle signature
- Defect diagnosis
  - Determine cause of enhanced RCS at isolated defect locations
- Defect RCS assessment
  - Assess impact of a specific defect on the overall vehicle signature
  - Verify effect of corrective action applied to a specific defect

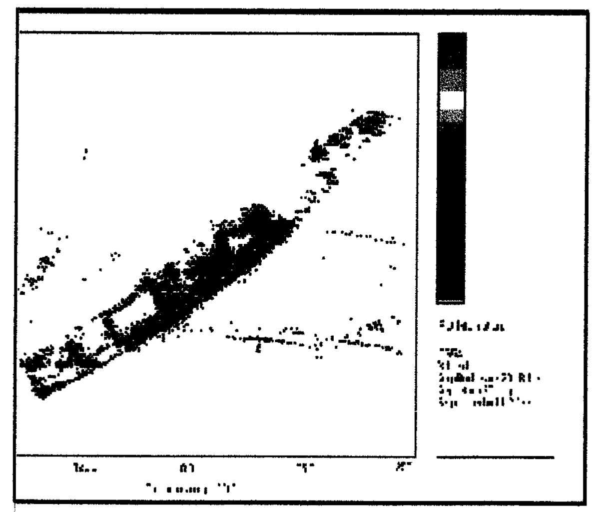
Radar Cross Section



Total Signature



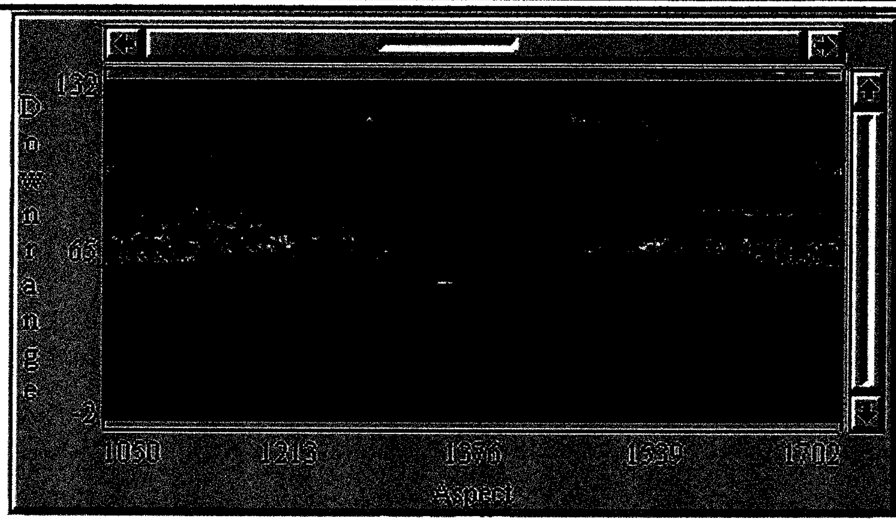
1-D RCS

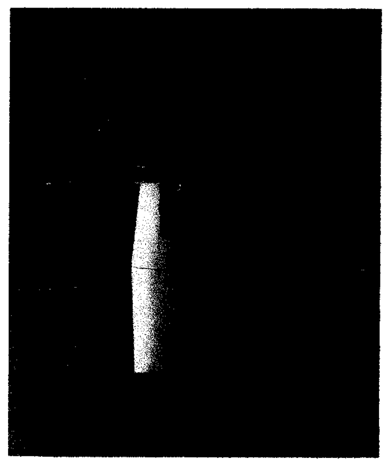


2-D Image

RCS data needed to assess survivability and maintain proper signature.

Downrange Image





Navy Requirements

- Aircraft aboard carrier
  (Navy JSF)
  - **All** constraints of carrier environment
- Aircraft in austere location
  (Marine Corps JSF)
- Ship
  - Dynamics of test
  - Physical size
  - Fixed site (today); organic to battlegroup (DD-21)
  - Range to item under test
  - Auxiliary data collected

Current Measurement System Shortcomings

- Size
- Speed
- Ease of use
- Unit cost
- Suitability for mission requirements (e.g. carrier environment)
- Integration with rest of architecture

Data Analysis Project

- **Purpose:** To develop a system which can measure an item and determine the signature health of that item with minimal human interaction
- **Tasks:**
  - Automatic anomaly detection software development
  - Measurements - Use the MHSR to measure a "pristine" item, add anomalies to that item and re-measure

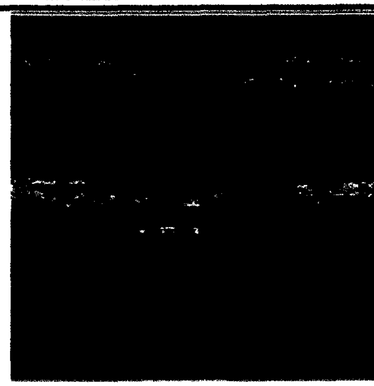
Automatic Anomaly Detection Task

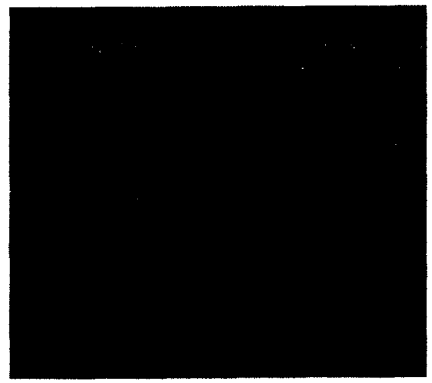
- Development of an anomaly detection and registration program using Artificial Intelligence techniques
- Knowledge Technologies International developed the ICON Downrange Profile System
  - Provides graphical facilities for loading reference and target data
  - Determines differences between reference and target data
  - Builds data abstractions of these differences
  - Automatically matches differences with known anomalies

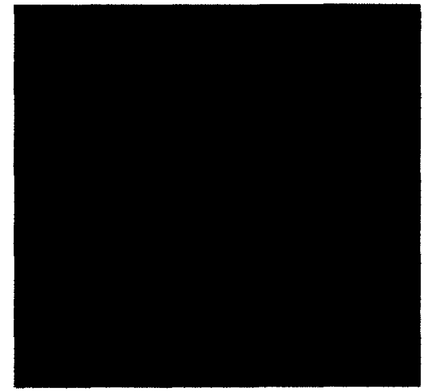
Levels of Data Abstraction

- Data-Point Level
  - Operations performed on individual points in the downrange profile
- Cluster Level
  - Groups of data points are created and operations are performed on individual clusters
- Anomaly Level
  - Groups of clusters are created as composite objects and operations are performed on groups of clusters

Image Analysis Details (Data-Point Level)







Reference Data → [redacted]

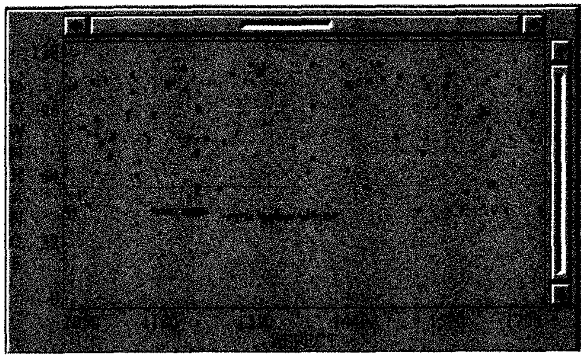
Target Data → [redacted]

→ [redacted]

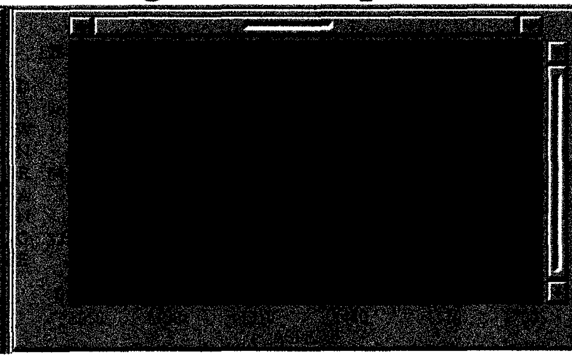
→ [redacted]

Cluster Analysis

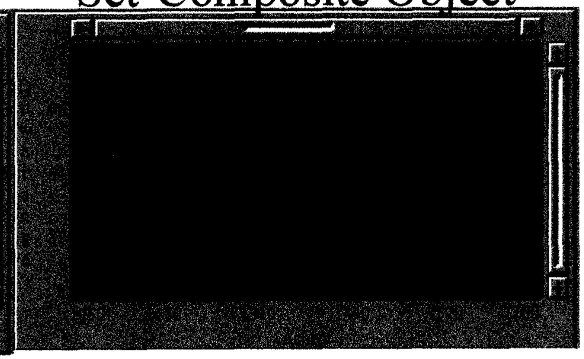
Generate
Base Clusters



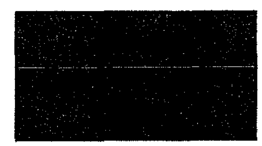
Merge and Despeckle



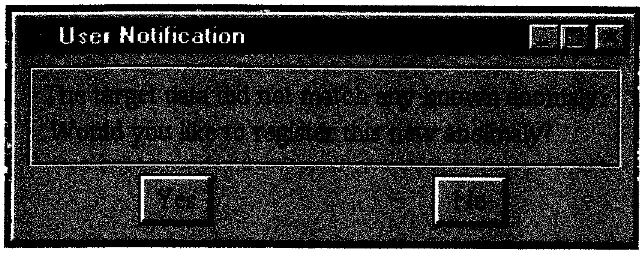
Generate
Set-Composite Object

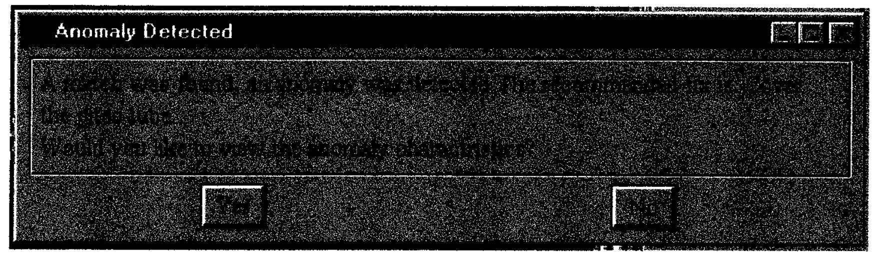


Generate Difference Clusters → Merge Clusters → Despeckle Clusters →



Anomaly Detection Details (Anomaly Level)





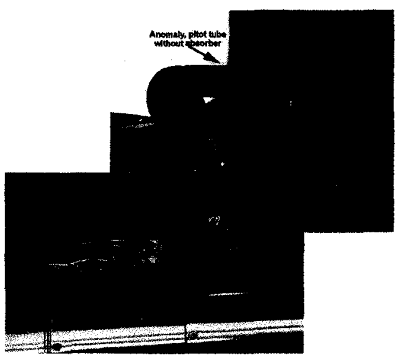
[redacted] ← No [redacted] Yes → [redacted]

↑

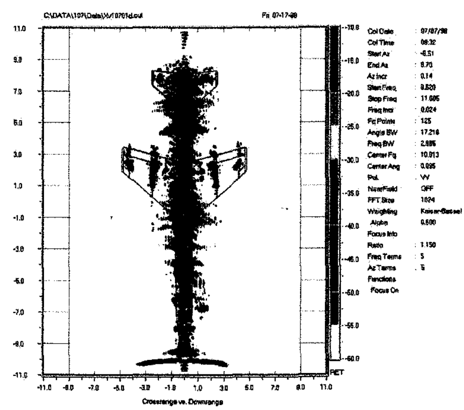
[redacted]

Validation

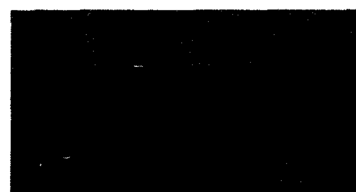
- To validate the usefulness of the software realistic data needs to be provided to the software programmers
- Measurement on the MQM-107
  - The MQM-107 is a target drone with a wingspan of 10’, length of 16 feet, and a weight of approx. 350lbs.



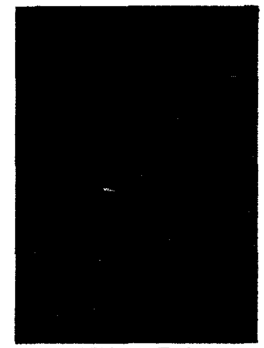
Pitot Tubes



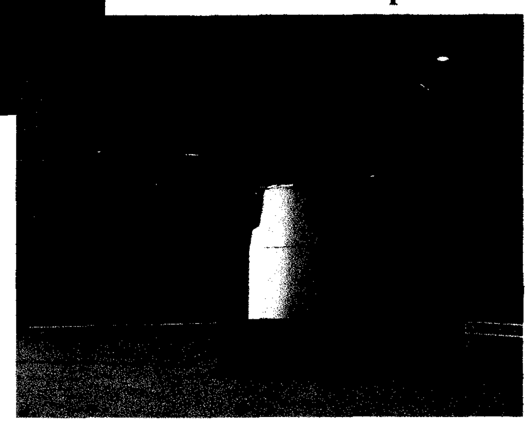
MQM-107 Data



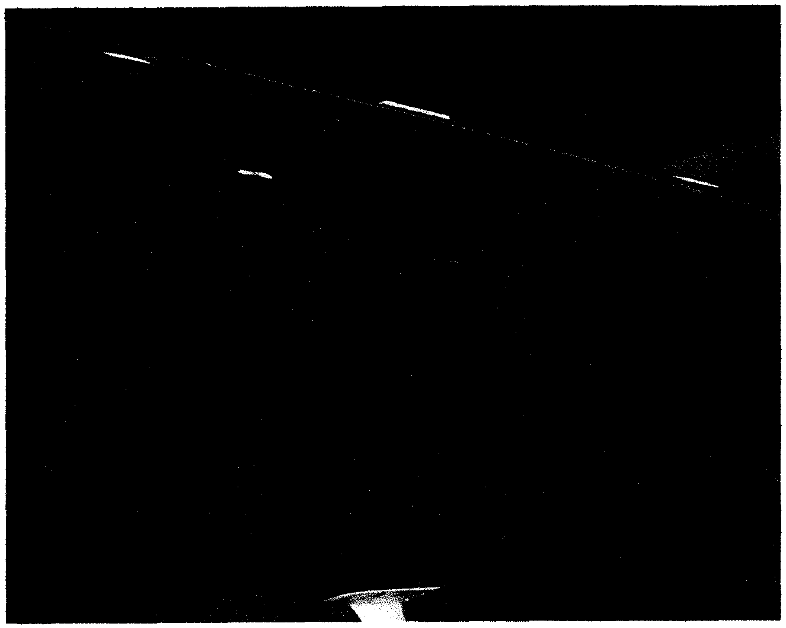
Wing Joint w/ Tape



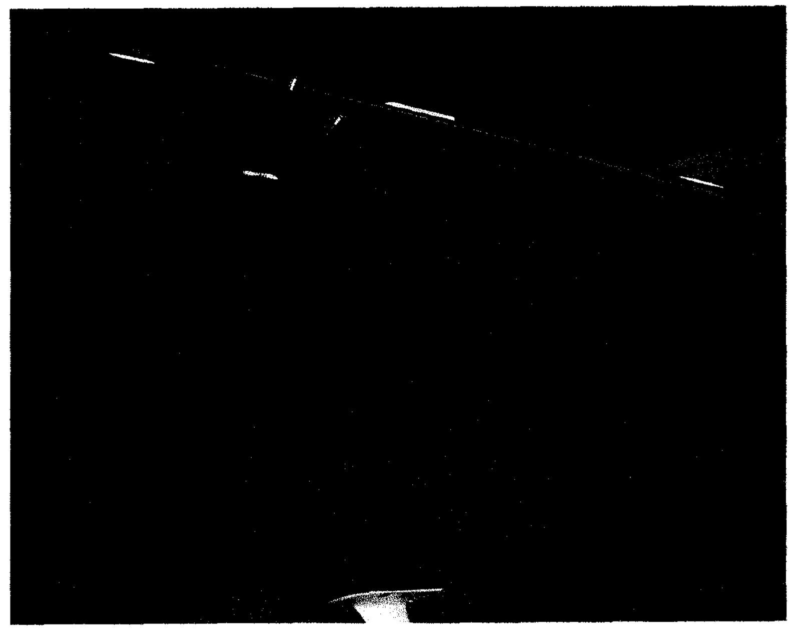
Wing Joint w/o Tape



Port Access Screws



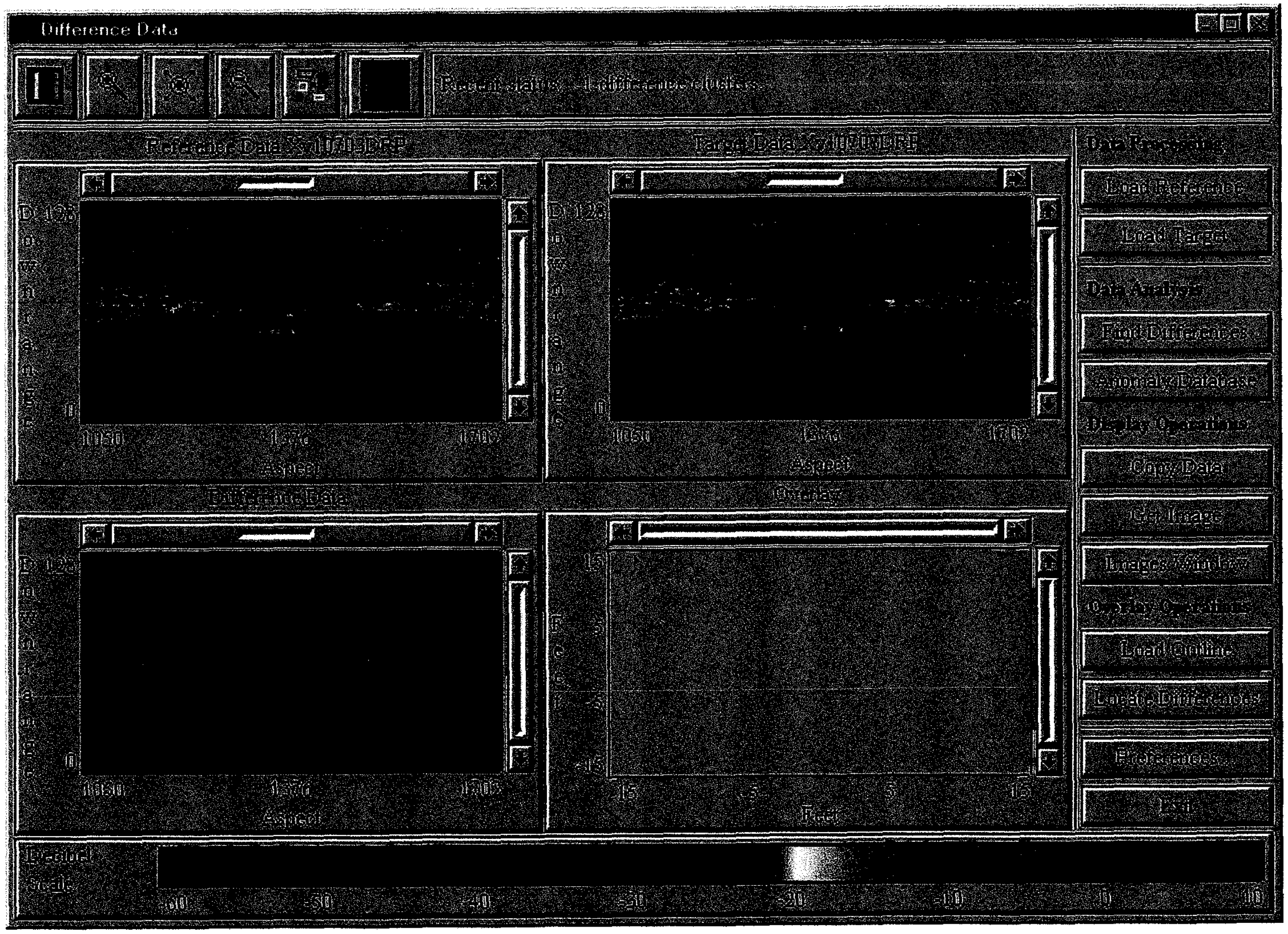
Access Screws In



Access Screws Out

Unclassified

Port Access Screws

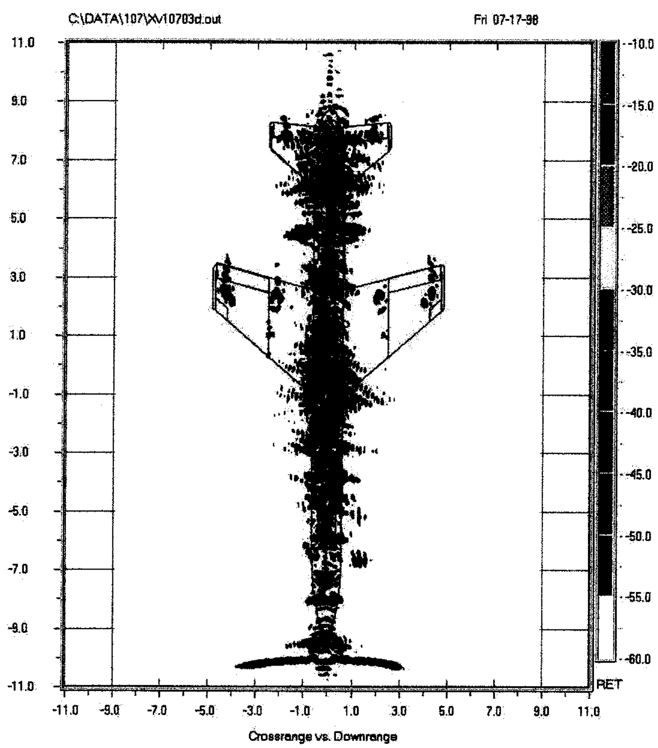


Unclassified

Unclassified

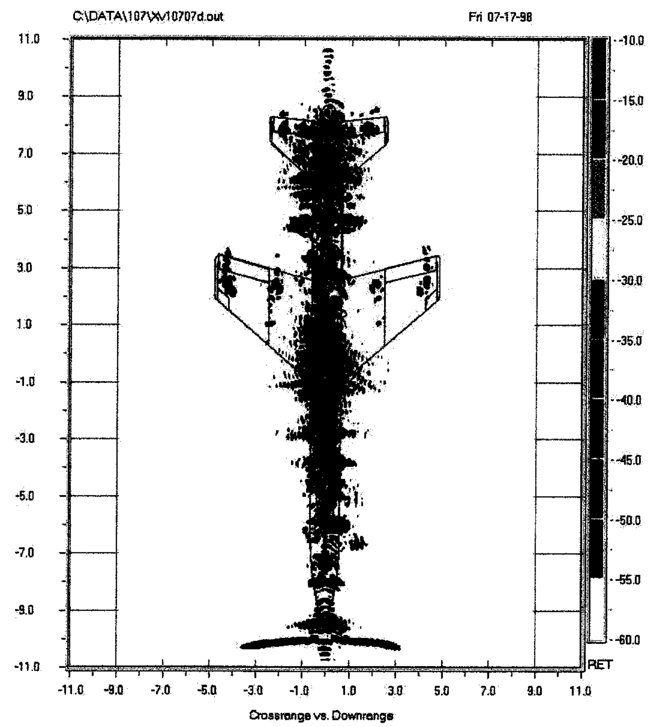
Port Access Screws

Baseline



Col Date	: 07/07/98
Col Time	: 10:33
Start Az	: -8.51
End Az	: 8.70
Az Incr	: 0.14
Start Freq	: 8.520
Stop Freq	: 11.505
Freq Incr	: 0.024
Fq Points	: 125
Angle BW	: 17.216
Freq BW	: 2.985
Center Fq	: 10.013
Center Ang	: 0.095
Pol.	: VV
NearField	: OFF
FFT Size	: 1024
Weighting	: Kaiser-Bessel
Alpha	: 0.500
Focus Info	
Ratio	: 1.150
Freq Terms	: 5
Az Terms	: 5
Functions	
Focus On	

Port Access Screws Out



Col Date	: 07/07/98
Col Time	: 11:02
Start Az	: -8.51
End Az	: 8.70
Az Incr	: 0.14
Start Freq	: 8.520
Stop Freq	: 11.505
Freq Incr	: 0.024
Fq Points	: 125
Angle BW	: 17.216
Freq BW	: 2.985
Center Fq	: 10.013
Center Ang	: 0.095
Pol.	: VV
NearField	: OFF
FFT Size	: 1024
Weighting	: Kaiser-Bessel
Alpha	: 0.500
Focus Info	
Ratio	: 1.150
Freq Terms	: 5
Az Terms	: 5
Functions	
Focus On	

Unclassified

Summary

- Initial efforts very successful
  - Distinguishable differences have been detected
  - Clusters generated coincided with perceived regions of differences in the target data
- Follow-on effort
  - In-house capability to operate and modify
  - More extensive database
  - Extend and optimize clustering techniques
  - Adapt to ISAR data
  - Automate parameter selection

Tunable, Narrowband Filter for LWIR Hyperspectral Imaging

Contract No.: F33615-99-C-1427
Technical Monitor: Mr. Ray Haren
Air Force Research Laboratory
Sensors Directorate
Targeting Branch
Wright-Patterson Air Force Base
Dayton, OH

Presented by:
Ed Johnson, Ph.D..
President, Ion Optics

Ion Optics, Inc.
411 Waverly Oaks Rd.
Suite 144
Waltham, MA 02452
(781) 788-8777

Ion Optics, Inc.

Contributors

A. Bodkin
J. Daly, M. Roderick
Ion Optics

R. Kerr, J. Noto,
Scientific Solutions
550 Middlesex St., Unit 210
North Chelmsford, MA 01863

A. Tuchman, AVI
138 Tappen St.
Brookline, MA

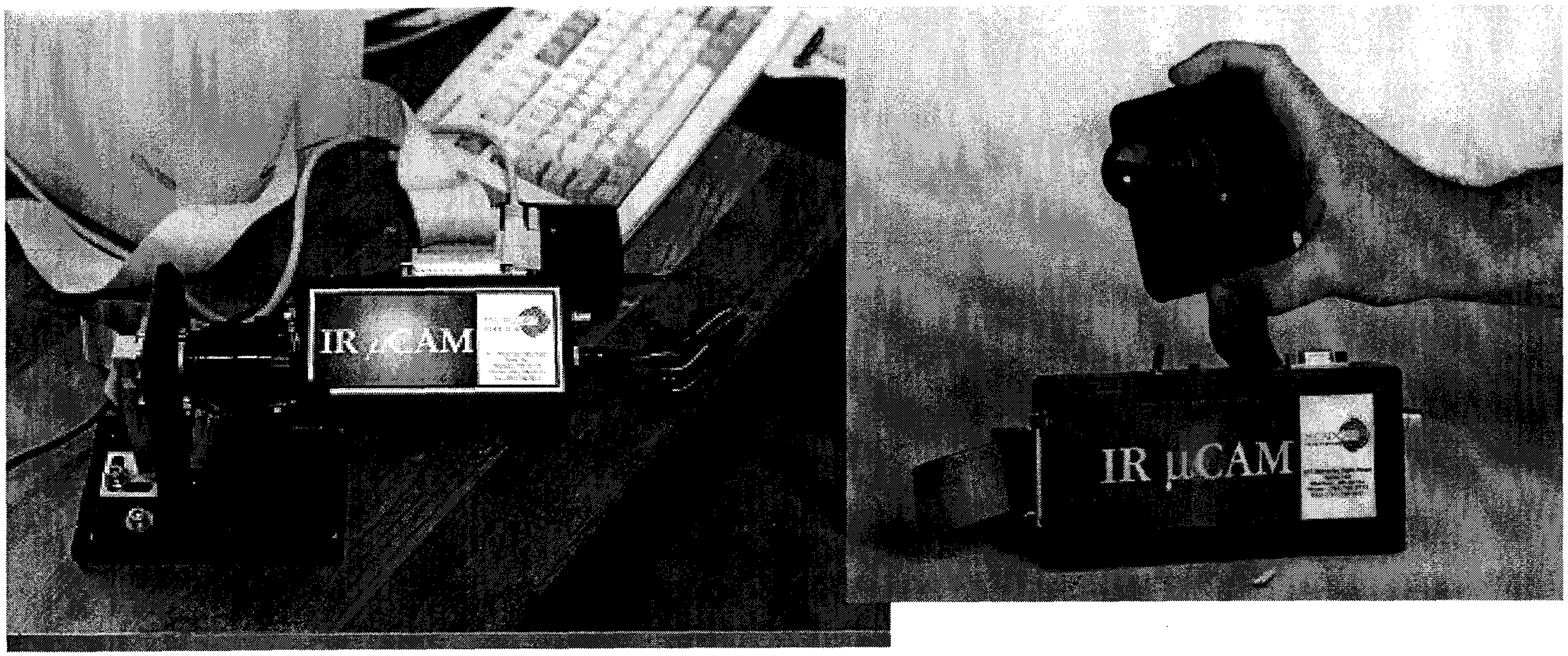
M. Eisman, B. Karch, R. Haren
USAF Research Laboratory
Wrigth-Patterson AFB
Dayton, OH

A.J. Ratkowski, R. Lockwood,
E.R. Huppi
USAF Research Laboratory
Hanscom AFB
Lexington, MA

Program Objectives

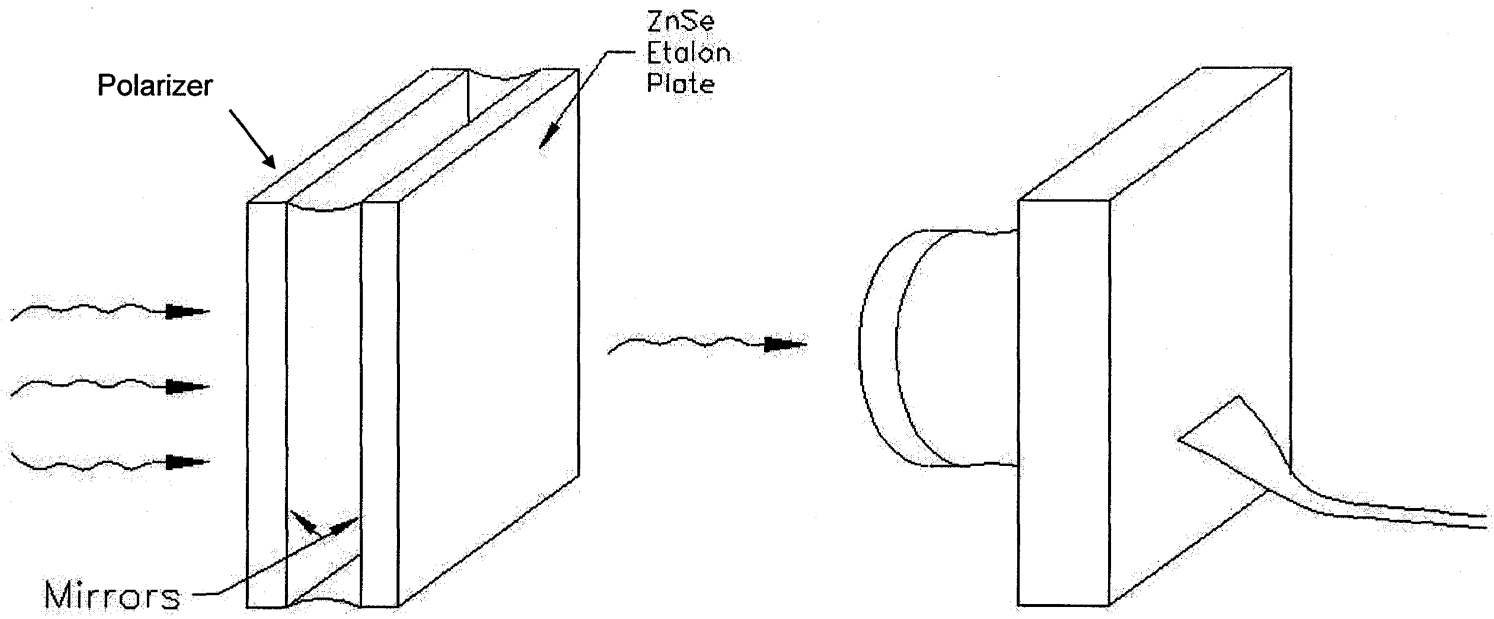
- Fabricate a prototype tunable filter based on liquid crystal-filled Fabry-Perot etalon (LCE).
- Enable voltage-controlled, tunable, narrow-band filtering at LWIR wavelengths
- Bandpass tunable at 60 Hz frame rates
- Enable rapid scene characterization for camouflaged target, or chemical identification
- Ability to build up Hyperspectral data cube with scanning software

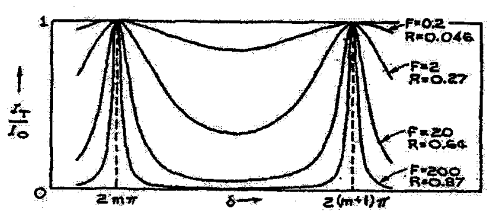
Digital IR Microcam Camera Set-up



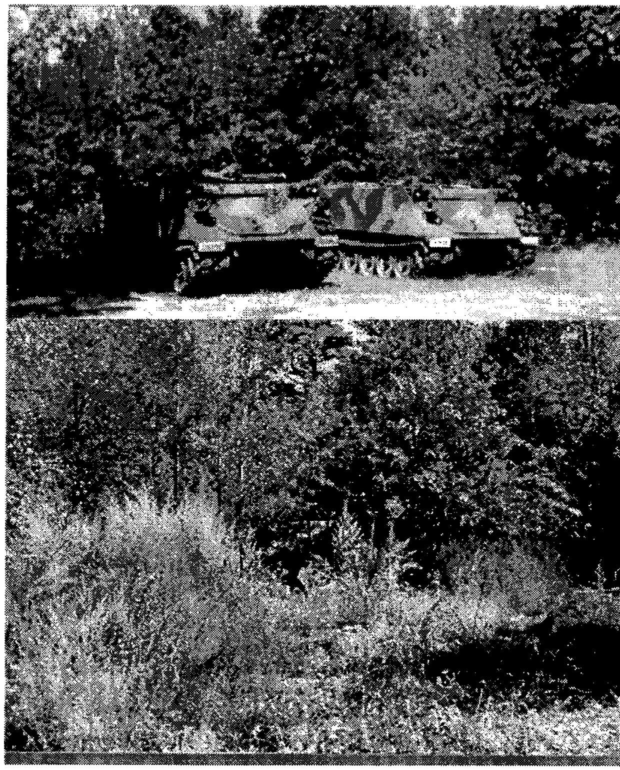
- Digital 8-12 micron IR Microcam Camera mated with a IR filter wheel holder.
- Using existing F1, 33°x25°field of view lens

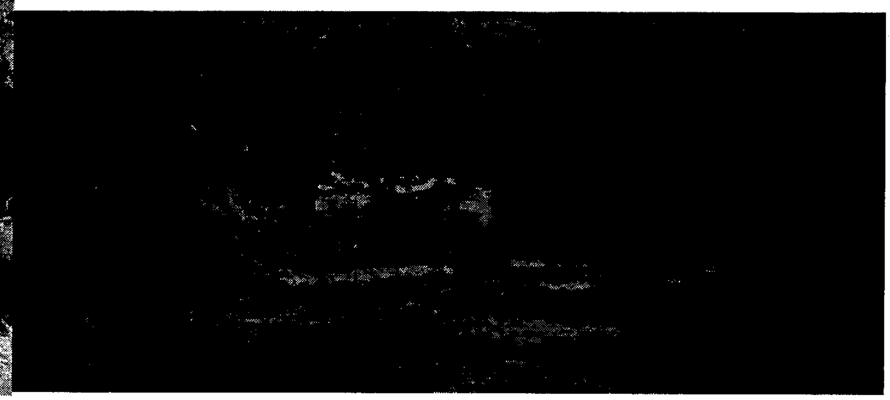
Hyperspectral Liquid Crystal Etalon



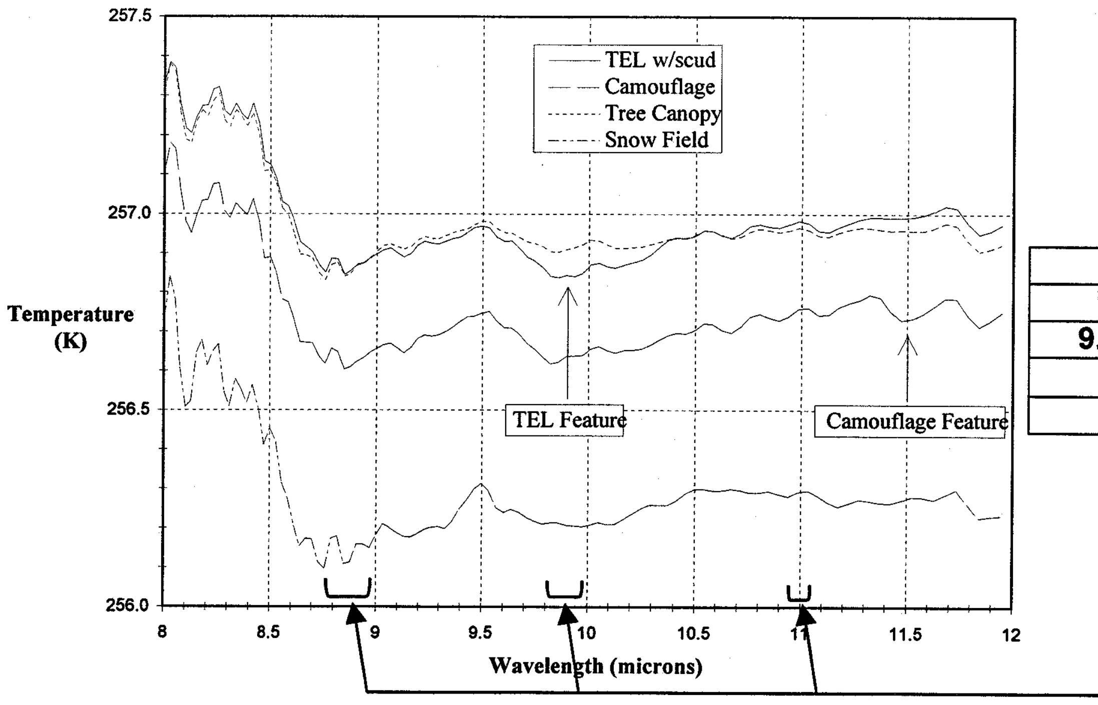


Potential Applications: Camouflage Penetration





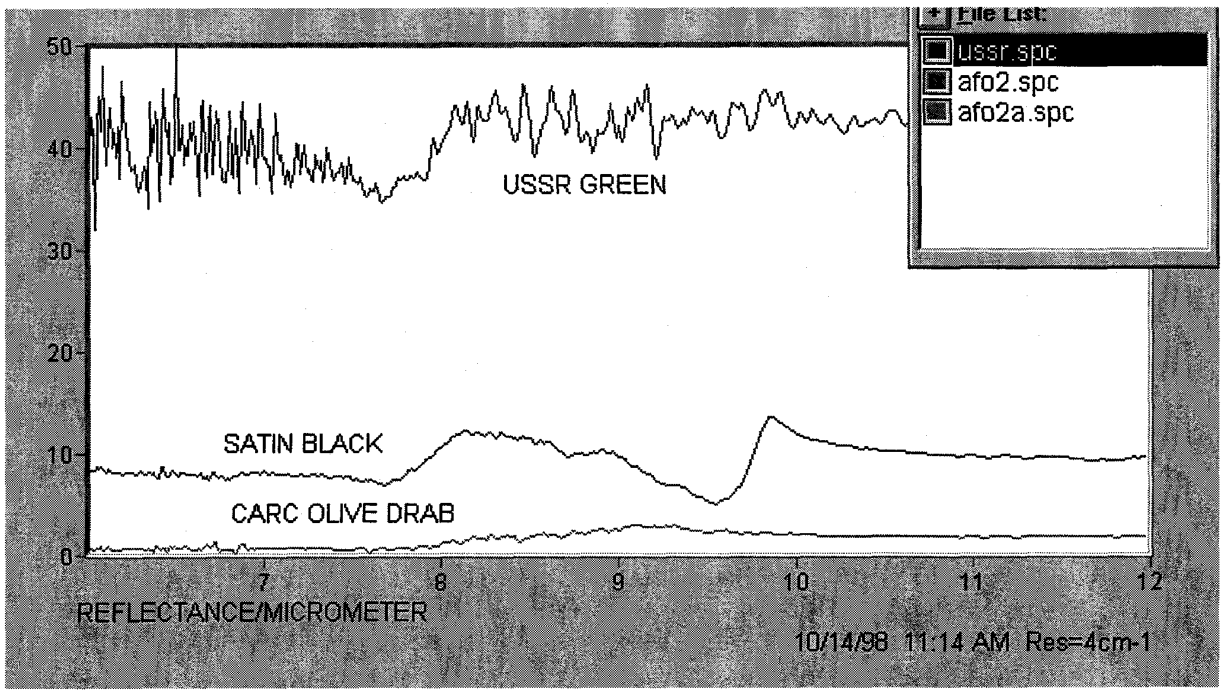
LWIR Comparison of Target & Background



Paint		Camo
U.S.	Foreign	Clutter
9.1-9.3	9.7-9.9	9.4-9.6
FWHM: 0.2 to 0.4 μm		
From J. Cedarquist		

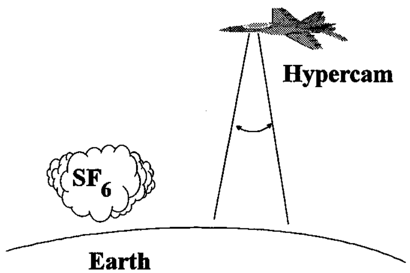
ERIM data shows typical paint, tree canopy and chamoflage spectra in the 8 to 12 um range. We selected filters to capture data around the SCUD spectral feature. This was compared to data from pictures on either side of the feature

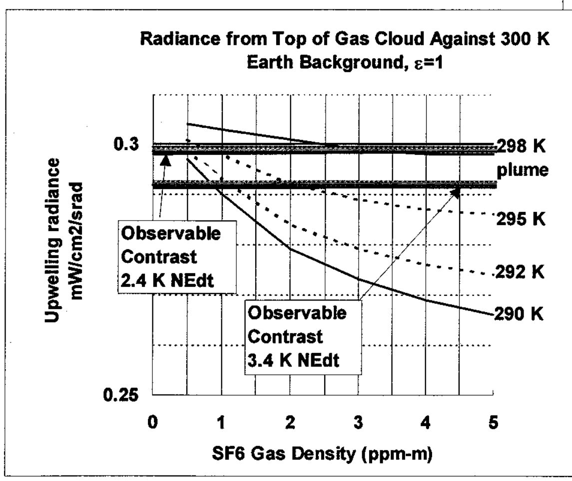
LWIR Comparison of Camouflage Paints

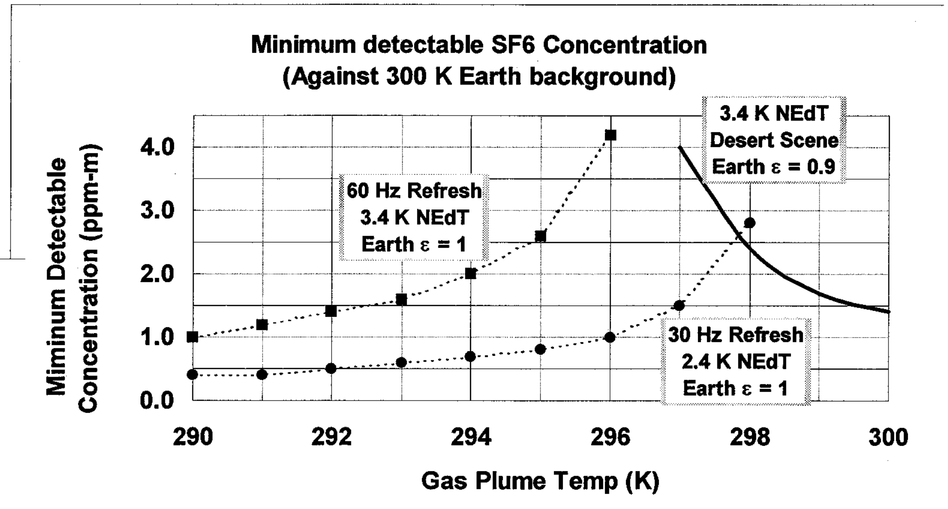


FTIR spectrum of camouflage paints. Our measured data of several paint samples shows that the spectral features are actually much larger then those provided by ERIM

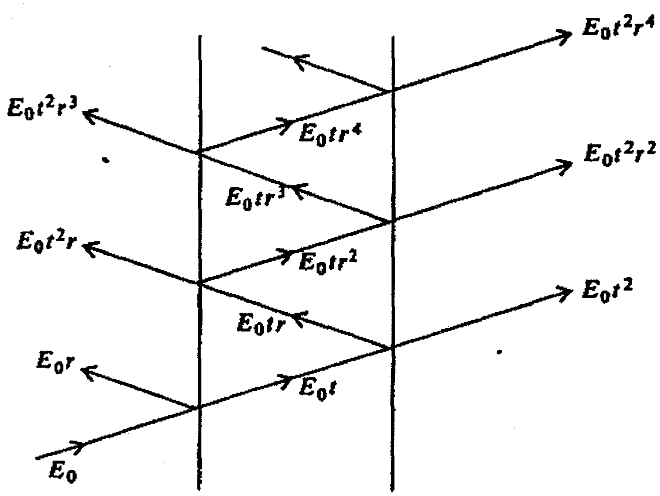
Potential Applications: Standoff Plume Detection







Fabry-Perot Etalon

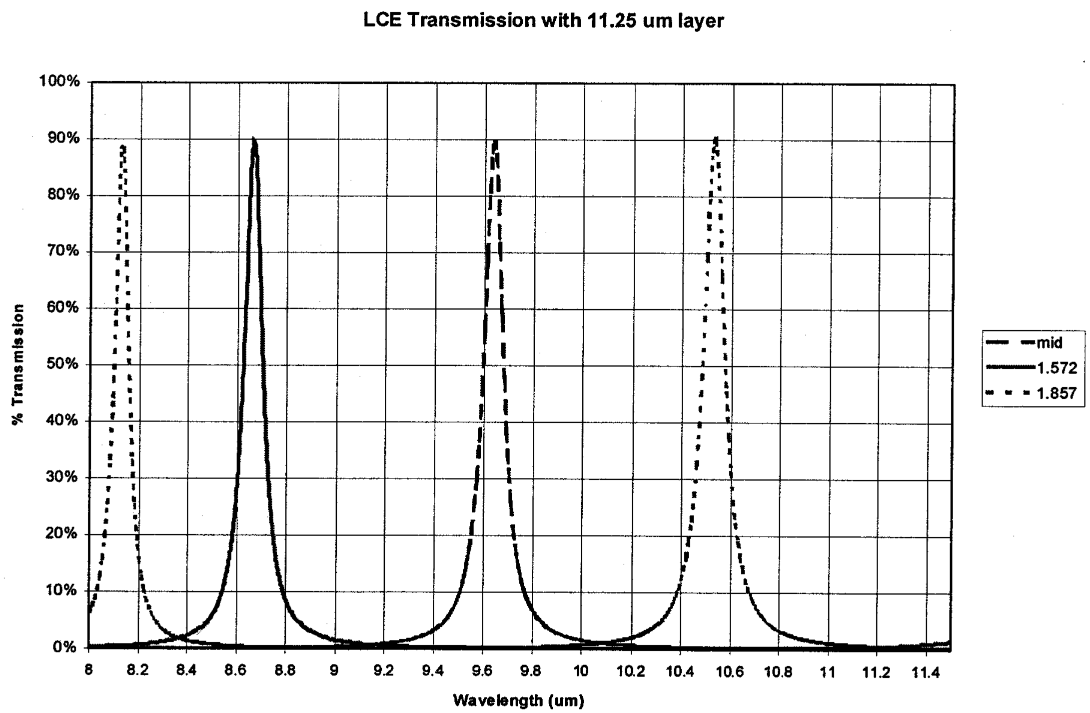


Phase difference between two successive rays is the optical path plus the phase shift from two reflections

$$Tx = \left[1 - \frac{A}{1-R}\right]^2 \cdot \left[\frac{1}{1+\left[\frac{4 \cdot R}{(1-R)^2}\right] \cdot \sin\left(\frac{2 \cdot \pi \cdot n(v) \cdot d \cdot \cos(\theta)}{\lambda_0} + \delta(\lambda)\right)^2}\right]$$

Where:
A = mirror absorption
R = mirror reflectivity
$n(v)$ = LC index of refraction, and is a function of applied voltage
d = LC thickness
λ_0 = free space wavelength of incident light
$\delta(\lambda)$ = phase shift on reflection
θ = incident angle of rays entering LC

LCE Transmission Model



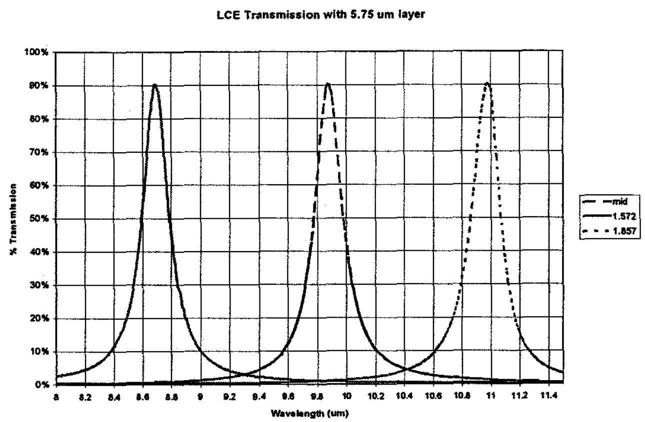
Three runs at n(v) = 1.572, mid, and 1.857

Transmission tuning range: 8.7 to 10.55 um

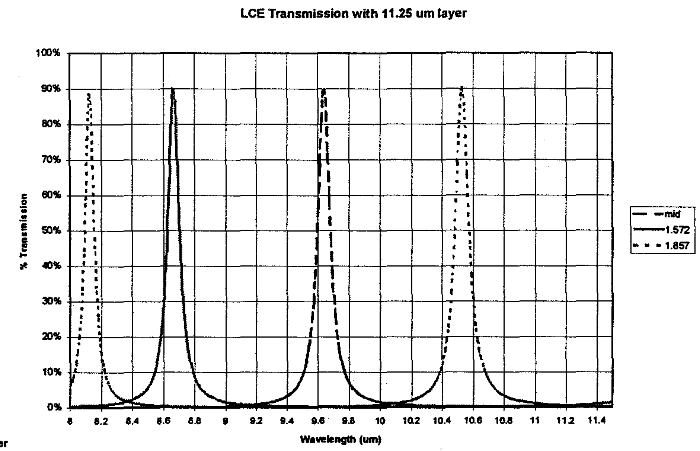
Bandpass: 0.1 um FWHM

Free Spectral Range: 2.4um

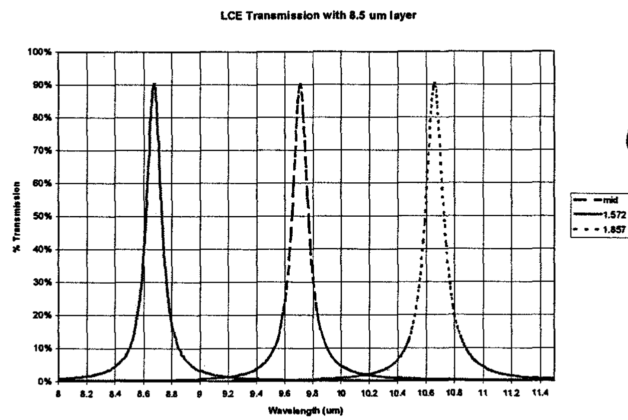
Changing Gap Changes Interference Order, Bandpass



5.75 um gap, 3rd order
0.22 um bandpass



11.25 um gap, 5th order
0.10 um bandpass



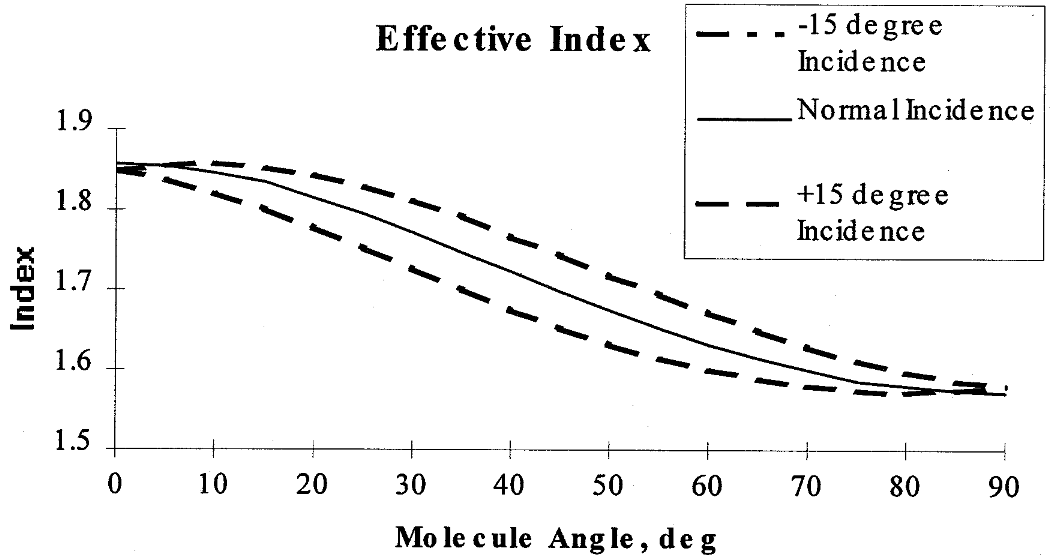
8.5 um gap, 4th order
0.13 um bandpass

Reflection phase is critical to LCE gap size

Wavelength (um)	Phase shift (deg)	Wavelength (um)	Phase shift (deg)
8	150.8551	9.6	176.7255
8.1	153.7042	9.7	177.7442
8.2	156.2353	9.8	178.7416
8.3	158.5013	9.9	179.7212
8.4	160.5476	10	180.6861
8.5	162.4122	10.1	181.6394
8.6	164.1258	10.2	182.5835
8.7	165.7132	10.3	183.5211
8.8	167.1947	10.4	184.4543
8.9	168.5868	10.5	185.3855
9	169.903	10.6	186.3166
9.1	171.1545	10.7	187.2498
9.2	172.3507	10.8	188.1869
9.3	173.4996	10.9	189.1298
9.4	174.608	11	190.0805
9.5	175.6816		

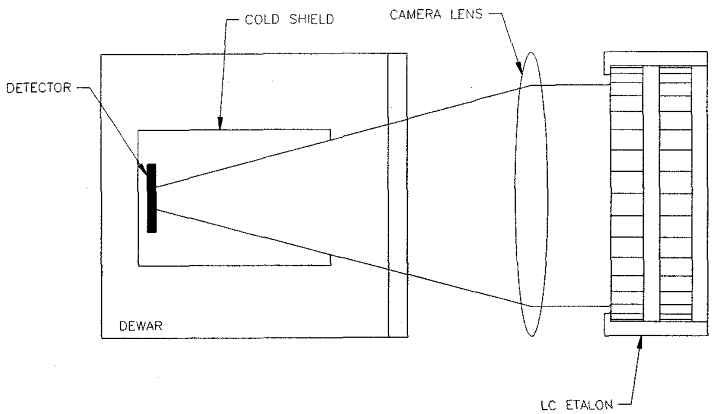
Calculated from thin film model of dielectric mirror. Phase shift is a function of wavelength.

Apparent Index Vs. Incidence Angle



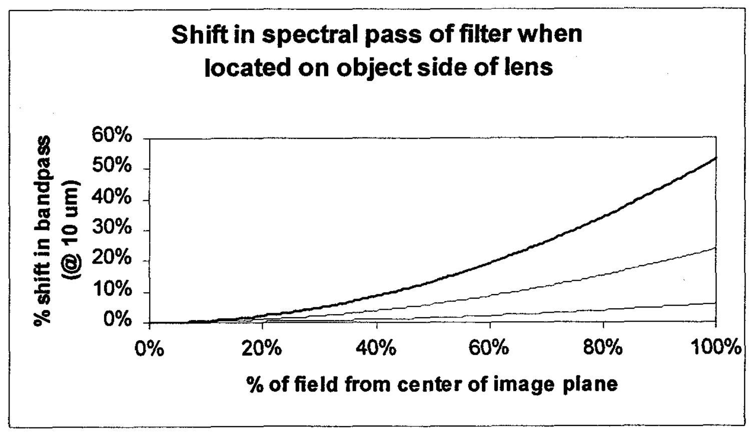
Plot of effective index of refraction of the LC, as the applied voltage causes the molecules to tilt. Note that the effective index also depends on the angle in which the light ray traverses the crystal.

System Issues

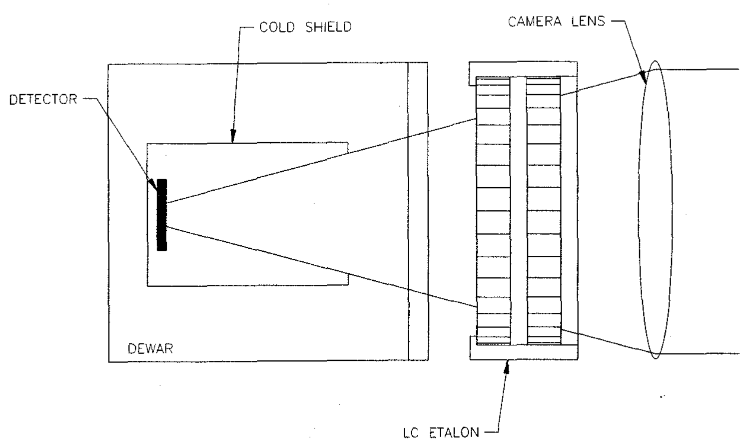


Filter before the lens

Bandpass peak shifts radial across FPA

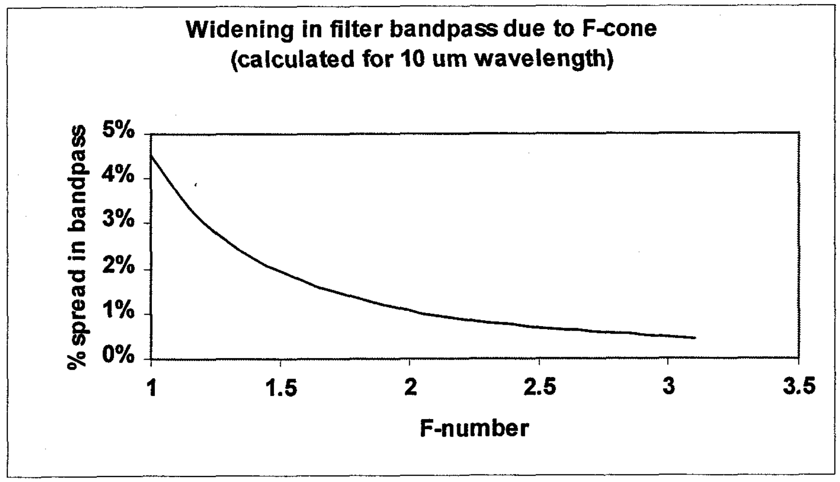


System Issues

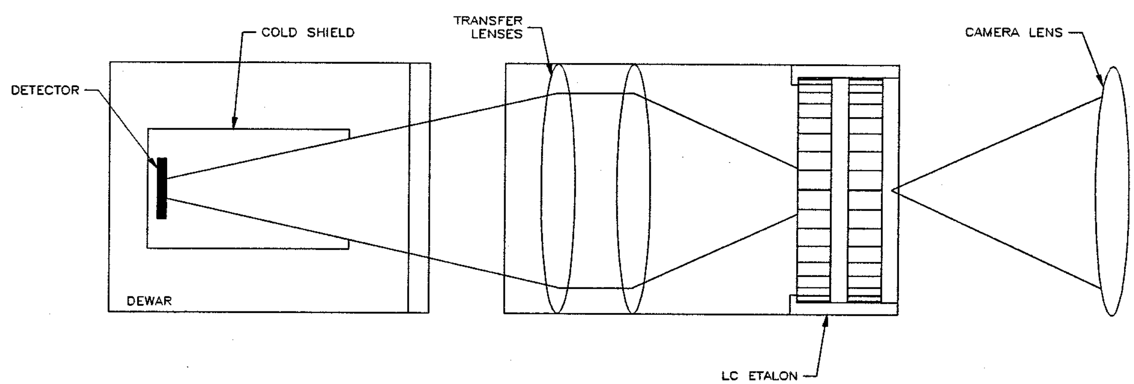


Filter after the lens

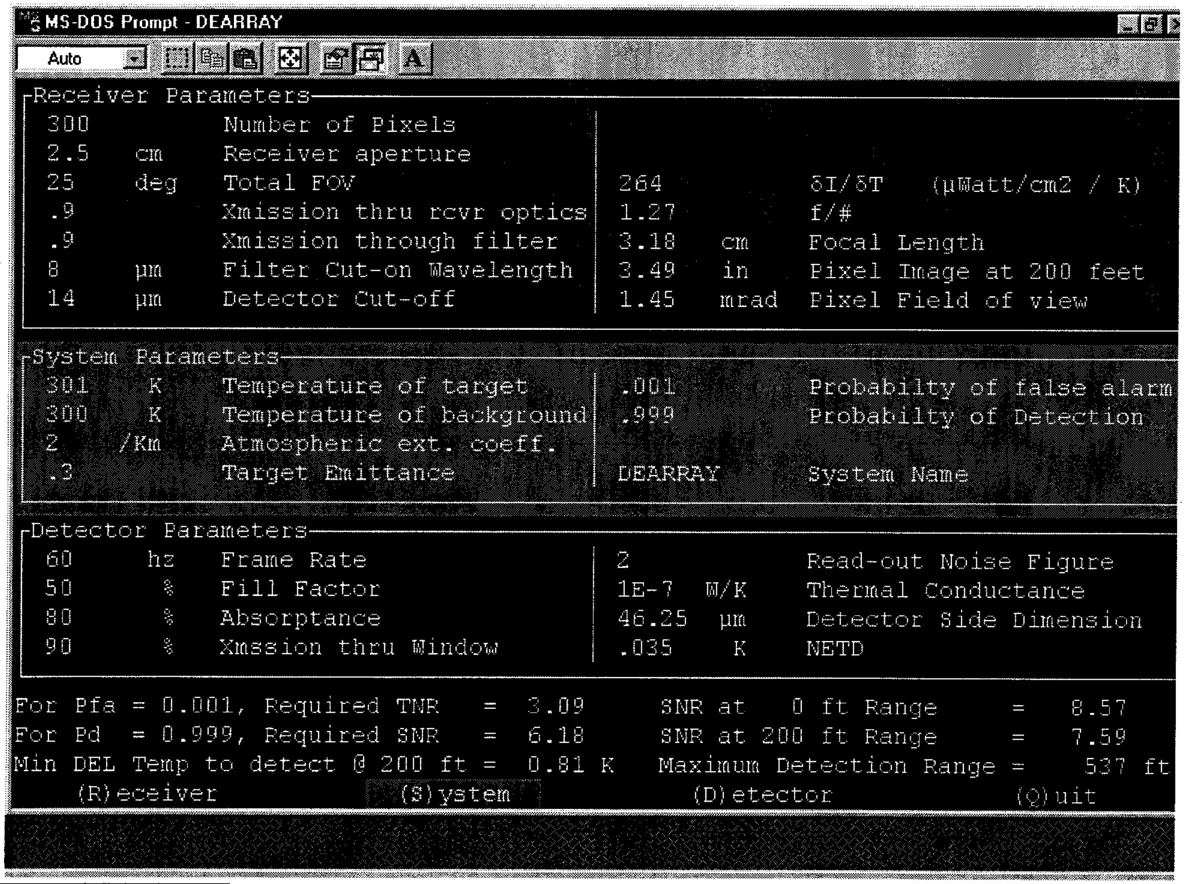
Bandpass widens depending on F#



System Design: Relay Reduces Stray Light

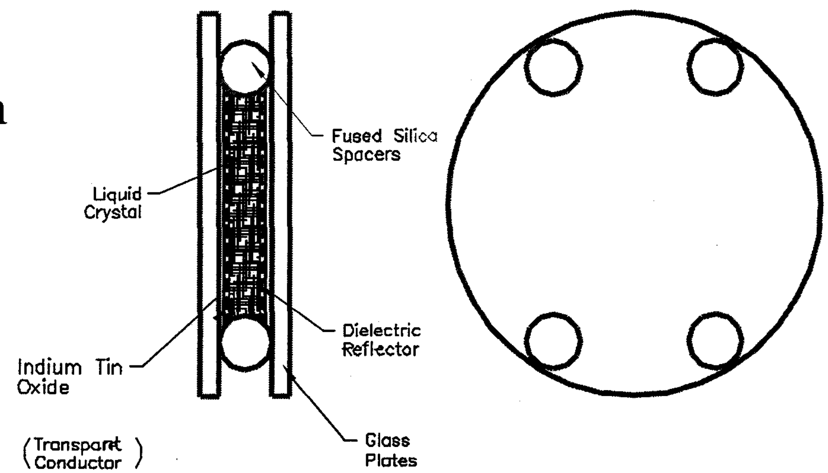


LCE/camera System Model



Liquid Crystal Etalon

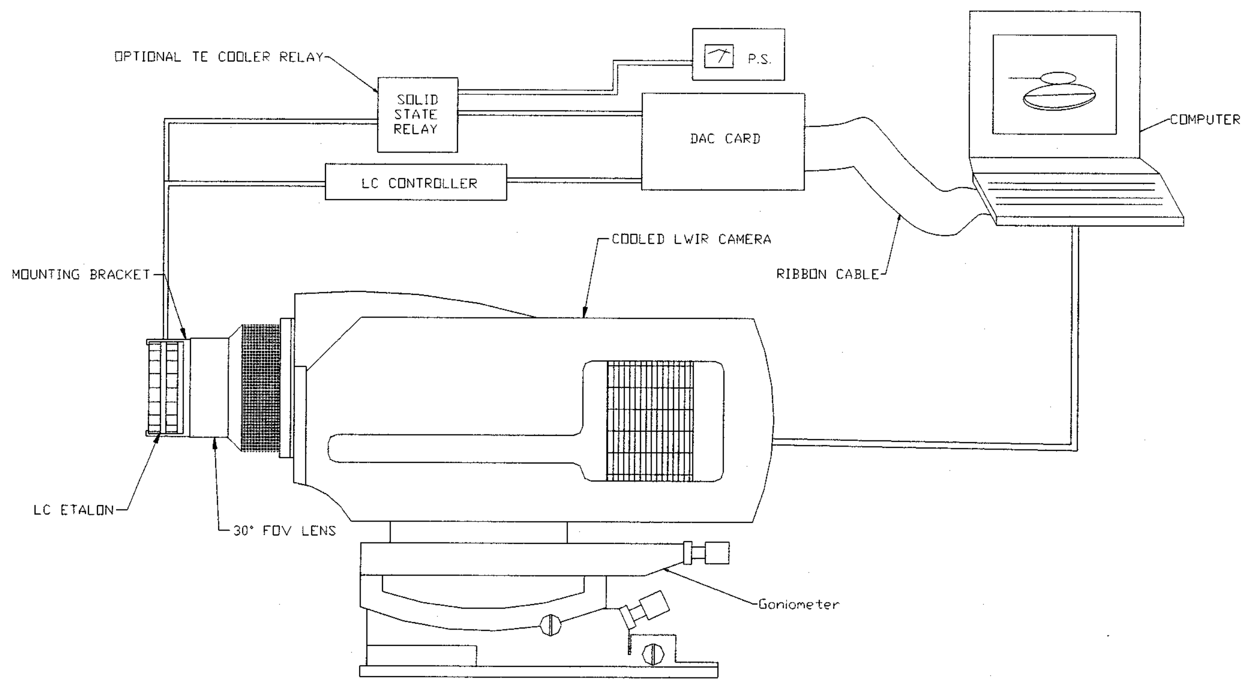
- Physical Diameter: 50.8 mm
- Clear Aperture: 45 mm
- Refractive Index: 1.57-1.86 μm
- Free Spectral Range: 2.4 μm
- Gap (LC thickness): 8.5μm
- Tuning range: 8.7 to 10.7 μm
- Bandpass FWHM: 0.13 μm
- Resolution: 1.3%
- Finesse ≥ 20
- Mirror material: ZnSe



Task 2: IR Camera Trade-off

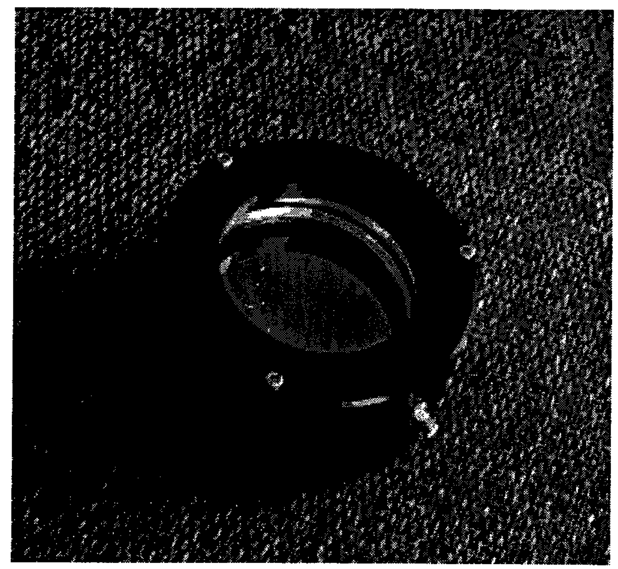
- *Model calculates MRTD at 200 ft. based on LCE properties and camera f#, FOV, spectral band pass, etc.*
- *Must determine system limitations with best available cameras*
- *Cameras to be considered: QWIP, HgCdTe, Microbolometer, BST*

LCE & Camera Test set-up



Conclusions

- ❑ ***Rapidly tunable narrow band LWIR filter***
- ❑ ***Convert LWIR camera to Hyperspectral imager***
- ❑ ***Create Hyper-data cube with scanning software***
- ❑ ***Applications include chemical and target identification***
- ❑ ***Suitable for terrestrial and space born applications***
- ❑ ***Prototypes available in 2000***



RADAR SIGNAL/IMAGE PROCESSING ENHANCEMENTS USING ALPHA-STABLE TECHNIQUES

Roger Lee, Radar Branch, Avionics Department, NAWC Aircraft Division

ABSTRACT

In conventional radar signal and image processing, the background clutter and noise are assumed to follow the Gaussian model. Recent research has found that many non-homogeneous types of clutter and noise, such as sea clutter, do not fit the Gaussian model well because of impulsive outliers or the so called "sea spike. These types of clutter and noise lend themselves to a heavy tail in amplitude distribution; consequently, the conventional matched filter does not perform well. Most recent research has shown that the α-stable model is a better model, and most radar clutter is modeled well by the α-stable statistics. A robust family of α-stable matched filters is a natural extension of the conventional matched filter with the capability of suppression the clutter to reveal targets. An optimal α-stable matched filter extracted from this family of filters is being developed in a simple closed form. This optimal α-stable matched filter significantly improves target detection in both simulated data and real clutter data. Moreover, the α-stable matched filter is computationally efficient. It can be applied in wide varieties of radar signal and image processing.

Introduction

In conventional radar signal/image processing, the background clutter/noise is assumed to follow the Gaussian model. Indeed Gaussian is a good model for homogeneous clutter/noise such as in the desert. Under this assumption, it has been shown that the conventional matched filter is optimal in target detection (Ref.[1]). However, recent research has found that many types of clutter/noise, such as sea clutter, do not fit the Gaussian model well because of impulsive outliers or the so called "sea spike" (Ref.[2]). These types of clutter/noise lend themselves to a heavy tail in amplitude distribution. Consequently, the conventional matched filter does not perform well. Radar engineers have been exploring other models such as the K-distribution or the Weibull distribution to fit these types of clutter/noise (Refs. [3], [4]). Most recent research has shown that the α–stable model is a better model and the associated α-stable matched filter enhances target detection in radar signal and image processing applications (Refs [5], [9]). Extended from the conventional matched filter, the α–stable m[1]atched filter is actually a family of matched filters lending itself to the robustness in filter optimization. This paper develops a simple close form in determining the optimal matched filter from the family of filters.

[1] Approved for public release : distribution is unlimited

Background : α-stable Model and α-stable Matched Filter

The symmetric α–stable model has three parameters (Ref. [6]); namely, the location parameter δ to specify the point of symmetry, the dispersion parameter γ to specify the spread of data around δ, and the characteristic exponent parameter α ($0 < \alpha \leq 2$) to specify the heaviness of the tail. It is to realize that, as a special case, when $\alpha = 2$ the α–stable model is a Gaussian model. Properties of the Gaussian model such as the bell shape, symmetry, and Central Limit Theorem carry naturally to the symmetric α-stable model. Thus, the α–stable model is a natural extension of the Gaussian model. It stands out from the Gaussian model by providing a unique parameter α that characterizes the heaviness of the tail of the clutter. It is shown in Ref. [5] that the real sea clutter called "HPC" (with radar look down angle of 8 degrees and sea state of 3) obtained from NSWC fits on the α-stable model better than the Gaussian model, the K-distribution, and the Weibull distribution. The α-stable model is also shown in Ref. [5] to fit four other types of real radar clutter data well.

Let u(t) be the radar transmit waveform and x(t) be the received signal. Then the conventional matched filter is expressed as :

$$u^*(-t) \otimes x(t) \quad \text{(1)}$$

and the α-stable matched filter (Ref [9]) is expressed as :

$$u^*(-t) \otimes \frac{x(t)}{|x(t)|^{2-p}} \quad \text{(2)}$$

where $\otimes$ is the convolution operation, * is the complex conjugate, and $0 < p \leq \alpha$.

It should be noted that the α-stable matched filter is actually a family of filters with parameter p, lending itself to the robustness in filter optimization. The α-stable matched filter distinguishes itself from the conventional one by multiplying a suppression factor $1/\,|x(t)|^{2-p}$ to the received signal for the purpose of suppressing the "spiky" clutter. For a Gaussian clutter (α = 2), the optimal matched filter is the one with $p = 2$ in Eq.(2). For a spikier clutter ($\alpha < 2$) the p corresponding to the optimal α-stable matched filter in Eq.(2) should be reduced accordingly to achieve the goal of suppressing the spikier clutter. Thus, the α–stable matched filter is a natural extension of the conventional matched filter with a parameter p as an extra dimension for detection optimization.

Performance of α-Stable Matched Filter

The simulated and real data from the popular linear chirp waveform radar are used to evaluate the performance of the α-stable matched filter (Ref [9]). Specifically, the NP-3 SAR

waveform with linear chirp rate of -30 MHz/sec, pulse duration of 4 micro-seconds, and sampling rate of 125 MHz is used in the simulation. The following simulation steps are designed:

1. Select, for each pulse, 512 range bins of simulated or real clutter data c(t) ;
2. Inject a target at 256-th range bin;
3. Form the received signal x(t) = s(t) + c(t), where s(t) is the simulated received target return from the transmitted waveform with amplitude adjusted to a desired SNR (signal to clutter/noise ratio);
4. Perform signal processing using the α-stable matched filter : y(t) = α(x(t)) as shown in Eq. (2);
5. Declare target detection only if |y(256)| is larger than a threshold;
6. Perform Monte Carlo for N pulses.

With a given SNR in step 3, the threshold needed in step 5 can be computed in accordance with selected PFAs (Probability of False Alarm). The Monte Carlo simulation is then performed to result in the ROC (Receiver Operating Characteristics) curves in terms of PFA vs. probability of detection. Figure 1 shows the ROC curves resulted from four α-stable matched filters using 1024 pulses of simulated clutter data with $\alpha = 1.74$, $\gamma = 0.97$, $\delta = 0.0$ (same α, γ and δ as the HPC sea clutter) and SNR = -20 dB. It is shown in Figure 1 that the probabilities of detection at PFA = 0.01 are 0.37, 0.80, 0.83, and 0.02 for $p = 0.5$, 1.0, 1.5, and 2, respectively. This simulation result shows that by using the α–stable matched filter with the parameter p in between 1 and 1.5 the probability of detection increases dramatically over the conventional matched filter ($p = 2$).

Note that Figures 1 only shows the performance of α-stable matched filters for four p values. Naturally, it is very desirable to obtain the p corresponding to the optimal matched filter. This paper develops a close form in determining optimal p.

Optimal α-Stable Matched Filter

As discussed earlier, the family of α-stable matched filters is defined in Eq. (2) with parameter p. It is unlikely that an analytic method can be obtained in determining the optimal matched filter from the family of filters. In this paper, Monte Carlo simulation approach is used to estimate the optimal p with a large number of trials, say N = 5000. Recall that if a clutter is well modeled by the α-stable statistics, it will be characterized by the three parameters α , γ, and δ, and hence the optimal matched filter p is a function of these three parameters. It is shown that actually the optimal α-stable matched filter depends only on the parameter α . Figure 2, in a simulation run with α = 1.5, 1.6, 1.7 1.8, 1.9, 1.92, 1.94, 1.96, 1.98, and 2.0, shows the performance curves of the family of α-stable matched filters in terms of probability of detection for different values of p. Through extended analysis of the performance curves, the following properties are observed:

1. the performance curves are smooth,
2. the α-stable matched filter can significantly outperforms the conventional matched filter (p=2); this is especially true for spikier clutter,
3. there is a plateau of optimal/near optimal region for each performance curve; i.e. there is a wide region of p for which the match filters are optimal or near optimal,
4. the optimal α-stable matched filter is independent of PFA,
5. the optimal α-stable matched filter is independent of SNR.

The above phenomena and analysis reveal that if radar clutter fits the α-stable model, the optimal α-stable matched filter is solely a function of the parameter α, i.e. $Po = f(\alpha)$, where Po is the p in Eq.(2) corresponding to the optimal matched filter. Naturally, it is very desirable to find a close form for the function f. For α = 1.5, 1.6, 1.7, 1.8, 1.9, 1.92, 1.94, 1.96, 1.98, and 2.0, the simulated optimal Po are indicated by "*" on the performance curves in Figure 2.. It is also observed that when $\alpha = 1.5$, $Po \sim 3\alpha/4 = 1.125$, and when $\alpha = 2$, $Po = 2$. One simple family (with parameter q > 1) of functions that pass through these two points and fits simulated optimal (α, p) data, indicated by "*" on the performance curves in Figure 2, is :

$$Po = f(\alpha) = 1.125 + 0.875 * (1 - (1 - 2 * (\alpha - 1.5))^{1/q}) \quad (3)$$

Through vast simulation runs, it is found that, with $q = 3.5$, Eq.(3) provides an excellent close form in estimating the optimal Po. These optimal Po via Eq.(3) for various α values are shown in Table 1. They are indicated by "o" on the performance curves in Figure 2. It is to note that even though the closed form optimal and the simulated optimal may not coincide with each other for all α-stable clutter they are both on the plateau of optimal/near optimal region. In fact, from Figure 2, the differences in probability of detection between them for all performance curves are all within 0.004. Thus the closed form optimal Po derived from Eq.(3) provides a simple and quick way to extract an optimal matched filter out of the entire family of α-stable matched filters. Using this optimal matched filter for the target detection processing via Eq.(2), the optimal α-stable matched filter outperforms the conventional matched filter significantly. Taking from the results shown in Figure 2, Table 1 shows the gain in probability of detection of the optimal α-stable matched filter over the conventional matched filter for different α-stable clutter. As expected, the spikier the clutter (smaller α value) the more gain the optimal matched filter produces.

α	1.5	1.6	1.7	1.8	1.9	1.92	1.94	1.96	1.98	2.0
Po (optimal)	1.125	1.179	1.244	1.327	1.448	1.482	1.523	1.575	1.651	2.0
SNR	-25	-23.5	-22	-20.5	-19	-19	-18.5	-18	-17.5	-17
Prob	0.763	0.706	0.637	0.581	0.553	0.480	0.527	0.558	0.589	0.640
Prob Gain	0.761	0.704	0.633	0.572	0.535	0.452	0.411	0.375	0.204	0

Table 1 Detection probability by the optimal matched filter vs. the conventional filter

Performance of Optimal α-Stable Matched Filter on Real Data

NP3-SAR (Synthetic Aperture Radar) data available in NAWCAD Radar Laboratory was used to evaluate the performance of the optimal α-stable matched filter on real data. A subset of L-band SAR sea clutter data known as the "Puerto Rico l9p5lhh" of size 512 range bins by 2048 pulses was observed. Fitting this sea clutter data by the α-stable model pulse by pulse, except for a few anomaly pulses, the parameter estimation of α is fairly consistent, with an average value of 1.759 and standard deviation of 0.1. With this α the corresponding optimal α-stable matched filter via Eq(3) is the one with $Po = 1.2897$. By using the Puerto Rico real data for Monte Carlo simulation, the optimal α-stable matched filter outperforms the conventional matched filter by a gain of 0.60 in probability of detection, which is comparable to the result shown in Table 1.

α-Stable Matched Filter for Image Formation

SAR provides 2-dimensional imagery, of which the axes are commonly referred to as the range and the azimuth. To form a SAR image two basic processing steps are needed; namely, the range compression and the azimuth compression. Each compression is processed using an appropriate matched filter. If the clutter of the image is spiky and the clutter fits a particular α-stable model well, then instead of using the conventional matched filter, one can expect that the use of appropriate α-stable matched filter(s) for either or both range and azimuth compression would result in improvement in target detection. To test the efficacy of the α-stable matched filter in image processing, a 512x512 simulated SAR raw data is created. The data contain simulated α-stable clutter pulse by pulse with $\alpha = 1.5$, and a simulated weak target at the center of the image with SNR = -35. The conventional image formation process is then performed on the data to form the image. The resulting image shows no target, just the noisy clutter.. An α-stable image formation matched filter consisting of the range compression filter with optimal Po derived from Eq.(3) and the conventional azimuth compression matched filter, is then applied to the same data. The resulting image shows a recognizable target with the clutter being successfully suppressed.

The above result is appealing but more work needs to be done in quantifying the performance of α-stable method versus the conventional method in terms of standard measurements such as location registration, phase accuracy, resolutions, mainlobe to sidelobe ratio, integrated mainlobe to sidelobe power ratio etc. In addition, real data should be tested to conclude the effectiveness of α-stable image formation matched filters.

Conclusion

In general most radar clutter are modeled by the α-stable statistics well. Robust family of α-stable matched filters is a natural extension of the conventional matched filter. An optimal α-stable matched filter is developed in a simple closed form in this paper. This optimal α-stable matched filter significantly improves target detection in probability of detection for simulated data as well as real clutter data. Moreover, the α-stable matched filter is computationally efficient. This technology can be used in wide varieties of radar signal and image processing. The process of implementing the α-stable technology in a platform is very simple; it can be outlined by the following three steps :

(a) periodically model the received signal to update the α parameter;
(b) compute a new optimal α-stable matched filter using Eq.(3);
(c) employ the new optimal α-stable matched filter (i.e. new optimal Po) in Eq.(2) for target detection.

References

[1] : L. L. Scharf, "*Statistical signal Processing : Detection, Estimation and Time Series Analysis*," Published by Addison Wesley, 1991.

[2] : G.W. Ewell, M. T. Tuley, and W. F. Horne, *"Temporal and spatial behavior of high-resolution sea clutter spikes,"* IEEE 1984 National Radar Conference, April 1984.

[3] : T. J. Nohara and S. Haykin, *"Canadian east coast radar trials and the K-distributed,"* IEE Proceedings-F, vol. 138, pp.80-88, April 1991.

[4] : G. Li and K.B. Yu, *"Modeling and simulation of coherent Weibull clutter,"* IEE Proceedings-F , vol. 136, pp.2-12, Jan. 1989.

[5] : SBIR Phase I Final Report : "*Advanced SAR Processing Techniques Based on Alpha-Stable Statistical Models,*" Prepared by Multispec Corporation, February 1997

[6] : Chrysostomos Nikias and Min Shao, "*Signal Processing with Alpha-Stable Distributions and Applications,*" Published by John Wiley & Sons, Inc. 1995

[7] : "*AN/APS-137B(V)5 Anti-Surface Warfare Improvement Program - SAR System/Segment Specification,*" Prepared by Texas Instruments Incorporated , 4 Oct 1996.

[8] : M.E. Tobin and M. Greenspan, "*Smuggling Interdiction using an Adaptation of the AN/APG-76 Multimode Radar*" IEEE AES System Magazine, November 1996.

[9] : Roger Lee, "Radar Signal/Image Processing Enhancement Using α-Stable Techniques", NAWCAD technical memorandum, 30 May 1997.

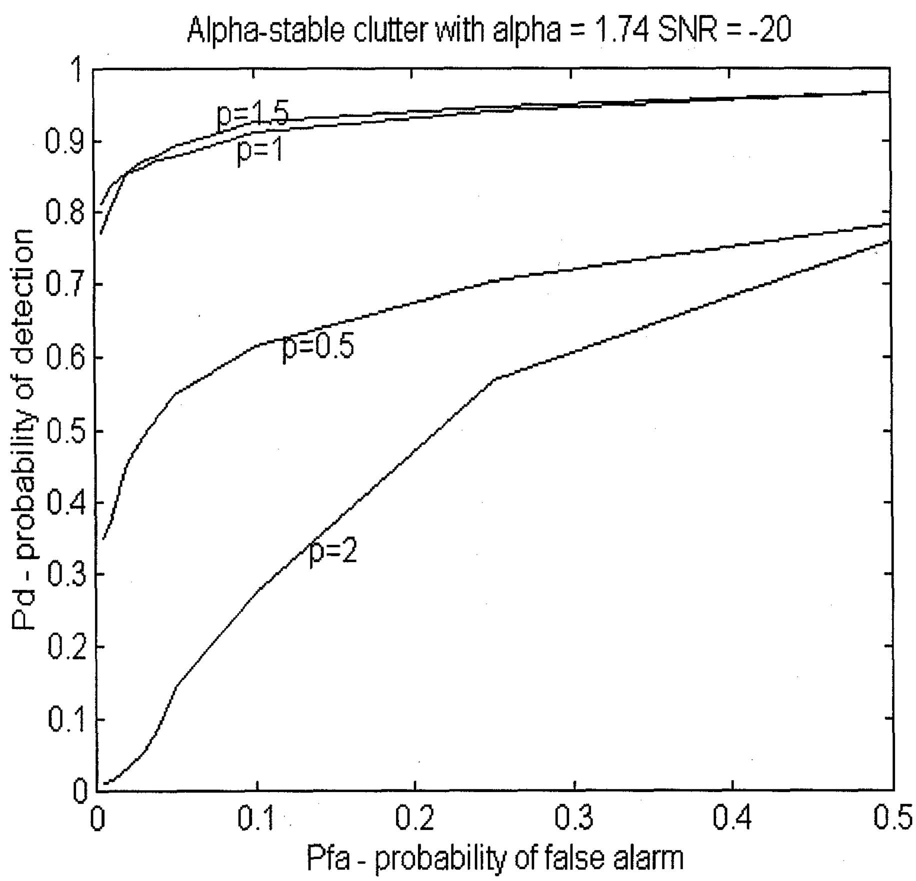


Figure 1 Performance of α–Stable Matched Filter on Simulated Clutter (PFA vs Pd)

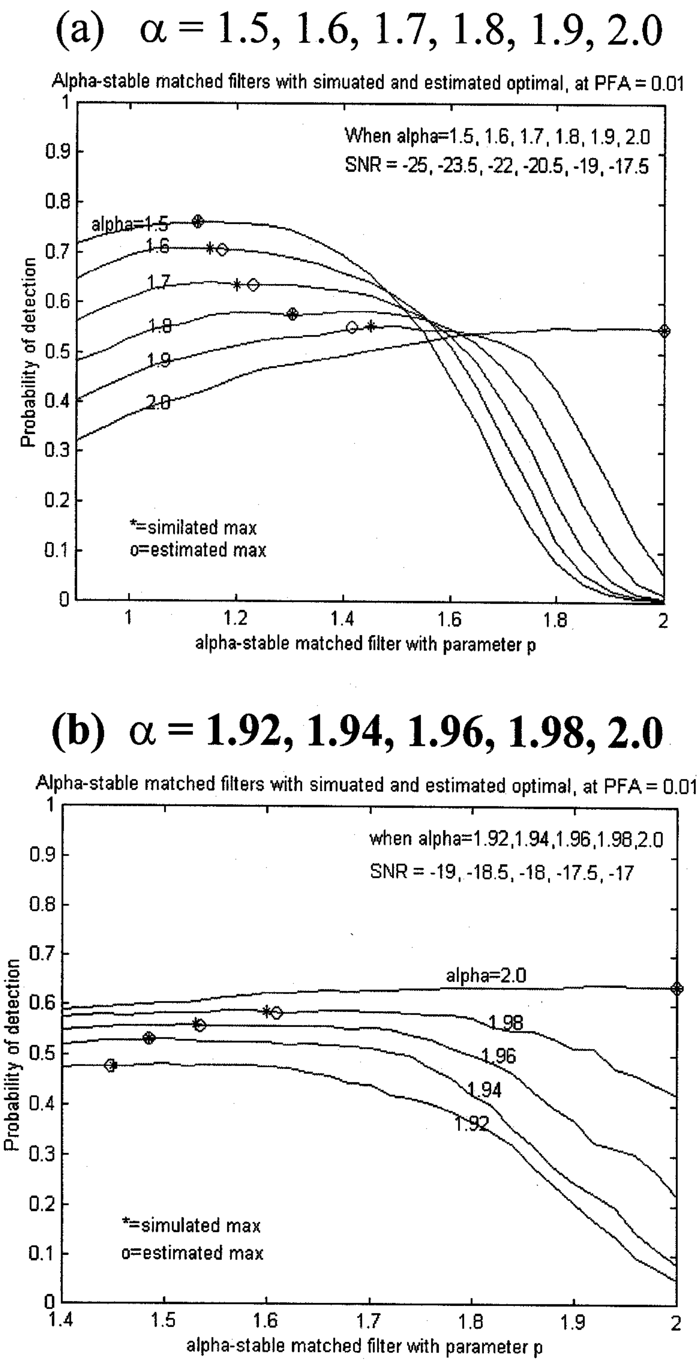


Figure 2. Performance of the family of α–Stable Matched Filters for simulated clutter with α = 1.5, 1.6, 1.7, 1.8, 1.9, 1.92, 1.94, 1.96, 1.98, and 2

3D Radar Signature Visualization of Air Vehicles

Tom Graves, Sensor Concepts, Inc.
Rob Hicks, Modern Technology Solutions, Inc.
Phil Soucy, Modern Technology Solutions, Inc.
Rick Renfro, Office of Naval Research

One of the challenges in displaying radar signature data is to present the data in an intuitive way so that the radar return levels identify the source of the radar returns. This paper describes a method of visualizing radar signature data using three-dimensional computer aided design (CAD) models.

Radar signature data can be presented in one dimension, as a dBsm level as a function of vehicle aspect angle. In a synthetic aperture radar image, data is presented in a two-dimensional image: as an intensity level represented by a color located in both vehicle down range and cross range. When the radar antennas are translated both vertically and horizontally, radar data is located three-dimensionally in down range, cross range, and vertical range. This is useful because it provides for a more precise location of point scatters, which would aid a technician tasked to repair a signature flaw. The point scatterer can be identified precisely because the ambiguity in vertical range is eliminated. Also, clutter due to ground bounce and bounce off of the ceiling can be separated from vehicle returns in the vertical dimension.

The Office of Naval Research and the Naval Air Warfare Center, Weapons Division, Advanced Antenna Technology Branch, China Lake, California, developed the Miniature High Speed Radar, or MHSR, used for collecting this 3D data. Sensor Concepts, Inc., Livermore, California, developed the 3D software. The data was collected using a T-38 at Edwards AFB, and a BQM-74E target drone at Naval Air Station Point Mugu.

The radar is a low-power linear FM homodyne radar, and is especially suited for collecting radar signature data of vehicles inside untreated hangars, due to its low output power and high accuracy. The MHSR was set up to image the aircraft at X-band, around a 10 GHz center frequency. Bandwidth was 3 GHz for the BQM-74E measurement, with a 20 ft by 30 ft by 30 ft image zone, and 2 to 3 inch resolution. Bandwidth was 1 GHz for the T-38 measurement in order to provide a larger image zone, and resulted in 5 to 6 inch resolution.

The T-38 was imaged while sitting on its landing gear in a maintenance hangar at Edwards AFB, as shown in Figure 1. Radar absorbent foam was used to block the return from the landing gear. The positioner translated the radar antennas 5 ft horizontally and 5 ft vertically.

The BQM-74 target drone was measured inside a maintenance hangar at Point Mugu. The drone was placed on a 5 ft column of expanded polystyrene foam. Radar absorbent foam was used to decrease the ground bounce in front of the drone.

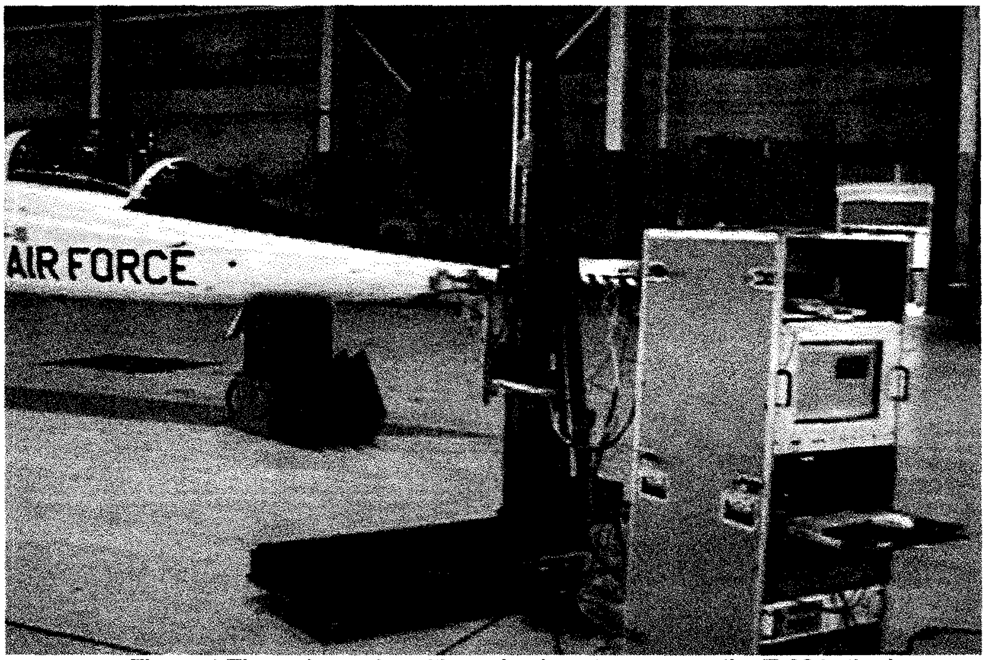


Figure 1 The radar and positioner in place to measure the T-38 in the hangar.

The 3D computer-aided design model was in the common .3ds file format. The number of facets is a measure of the complexity of CAD models. The T-38 model, shown in Figure 2, had over 2000 facets. The models were complex enough to accurately represent the aircraft without being so complex as to unnecessarily slow down the software that mapped the returns to the surface of the CAD model. The software used to create, manipulate, and display 3D models was VRT: a virtual reality software that is available commercially from Superscape.

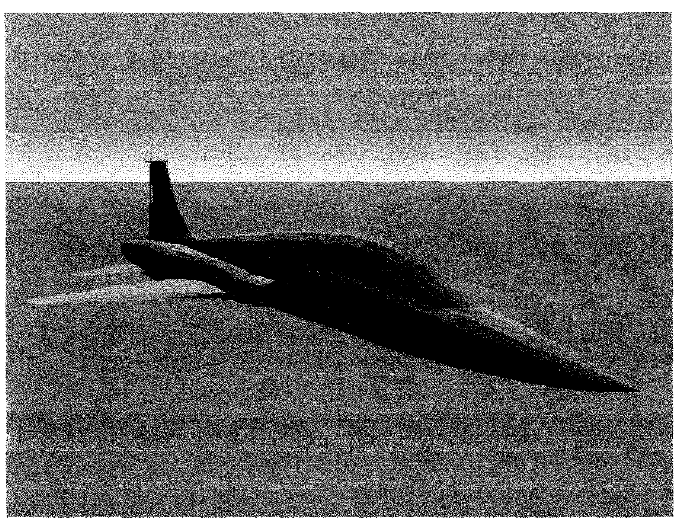


Figure 2. The 3D CAD model of the T-38 as depicted using VRT software.

The 3D-image visualization process, depicted in Figure 3, begins by creating or importing the CAD model of the aircraft into the VRT virtual reality software. The 3D CAD model is aligned to the 2D overlay used to map the MHSR data in cross range and down range. Then the data

collected by the MHSR is defined in cross range, downrange, and vertical range. The data is then mapped where it intersects with the CAD model surface, using a texture approach as shown in Figure 4. The texture approach maps pixels of color based on the resolution size of the radar data rather than only one color per CAD model facet. This approach permits depiction of the radar data to be independent of the CAD model facet size.

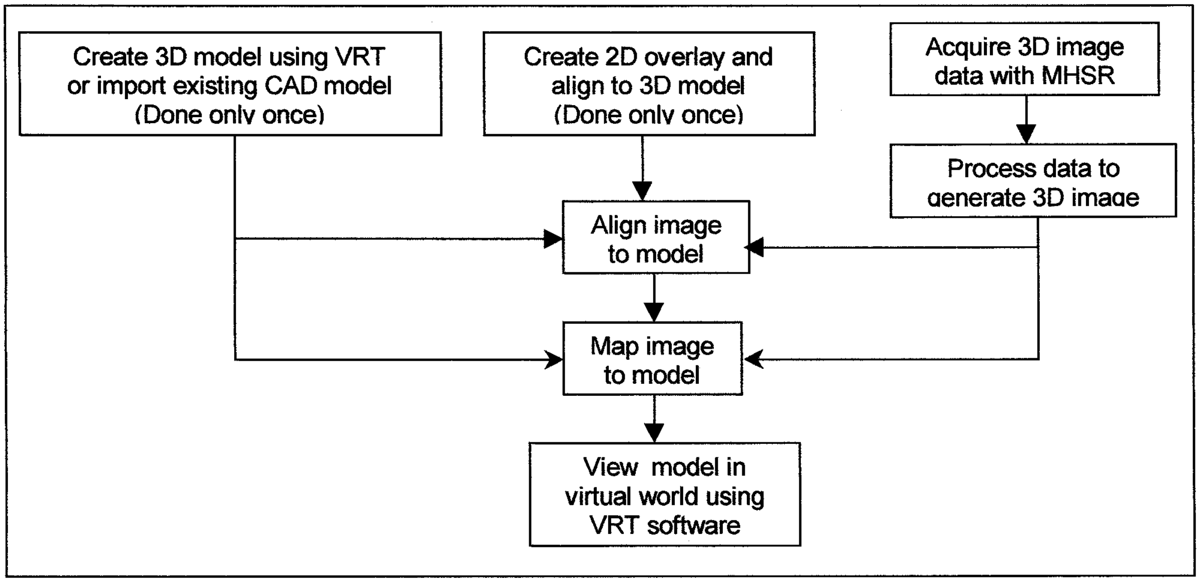


Figure 3. Procedure used to map radar signature data on a 3D model.

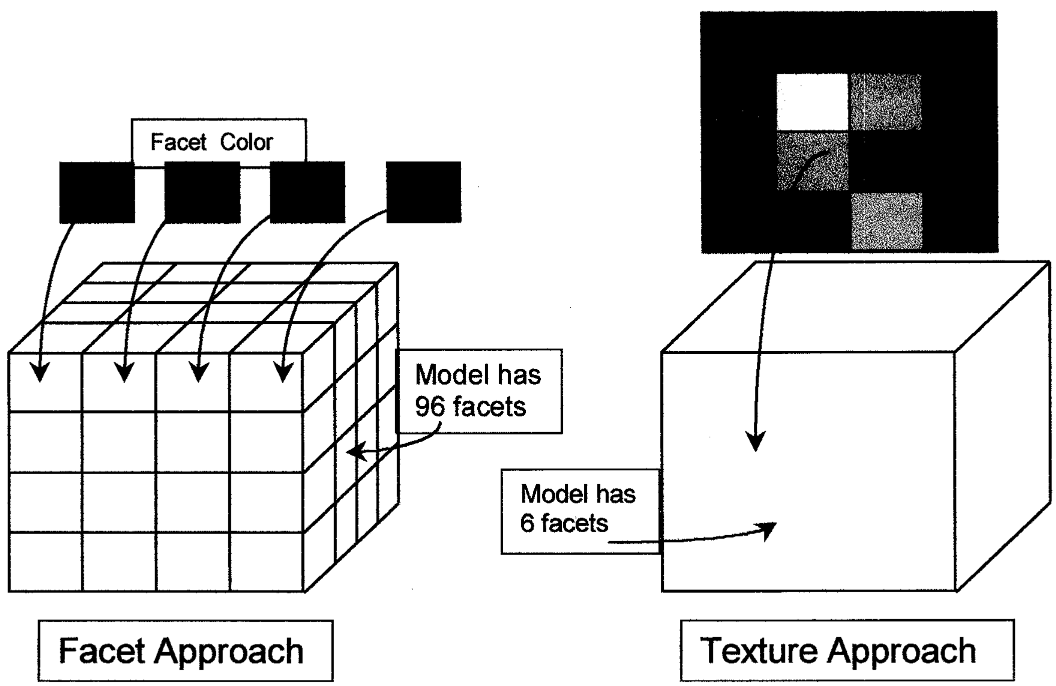


Figure 4. The texture approach to mapping colors to the 3D model is independent of facet size.

The VRT software then creates bitmaps of the pixels that map onto the facets of the CAD model. The VRT software also provides the capability to view the CAD model in 3D perspective and show it from any viewing angle.

Shown in Figure 5 is a typical 2D image created from MHSR data showing the outline of the T-38 in cross range and downrange. Note that all returns in vertical range collapse onto the display plane. Some radar return could come from reflections from the ceiling or floor, and would be mapped onto the aircraft outline.

Using 3D data eliminates the vertical range ambiguity problem, because returns are mapped in the vertical dimension as well as in cross range and downrange.

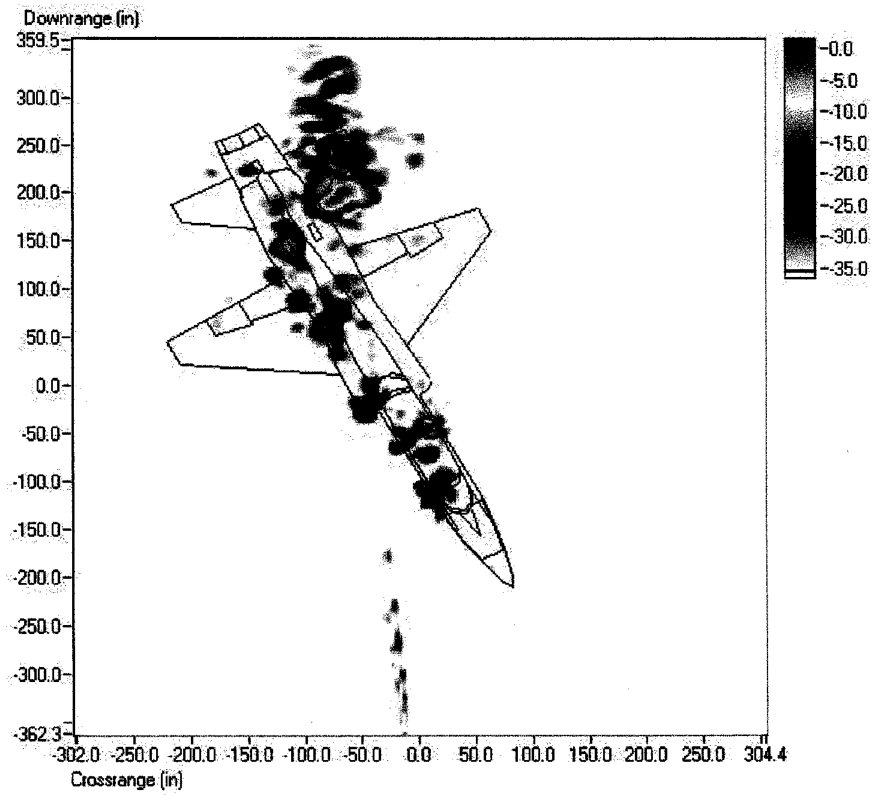


Figure 5. Typical 2D image using MHSR data.

The VRT software was used to generate the CAD model in Figure 6. This figure depicts the returns painted onto the external facets of the CAD model of the BQM-74E. Note the large return from the nose area. Note also that the return due to the mounting lugs and parachute cable are mapped to the top of the vehicle.

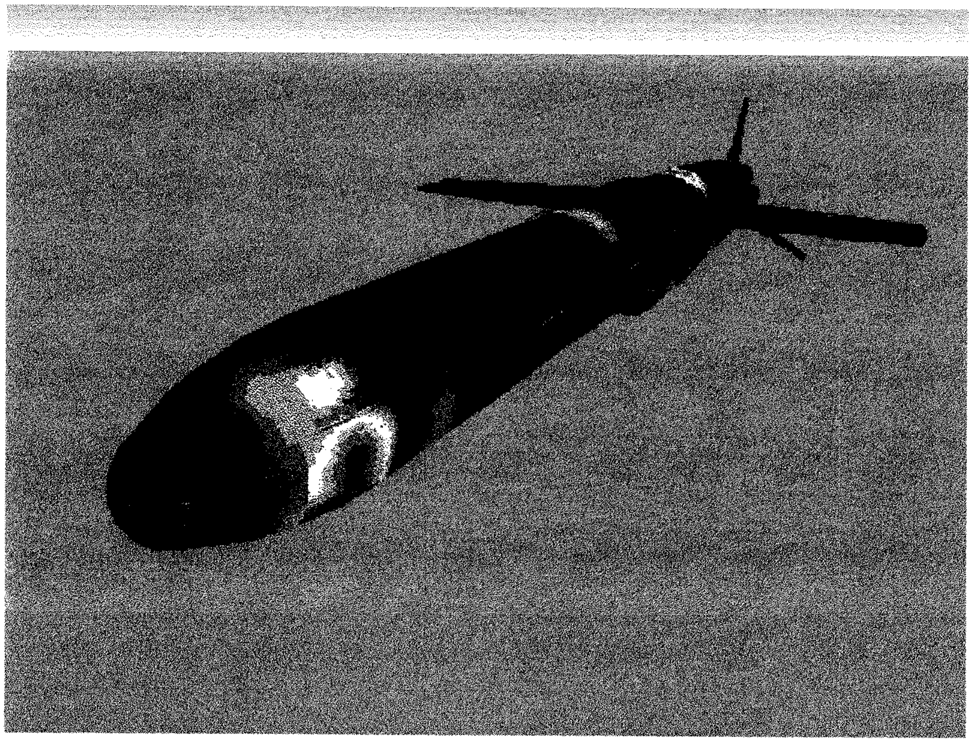


Figure 6. BQM-74E model with radar returns mapped onto the surface.

Figure 7 illustrates a T-38 model with the radar returns mapped on it. The engine inlets and canopy were covered with RAM to reduce their returns. The left view shows returns mapped to the top of the wing, and the right view shows the returns mapped to the bottom of the wing, clearly showing the effect of the landing gear and flap brackets.

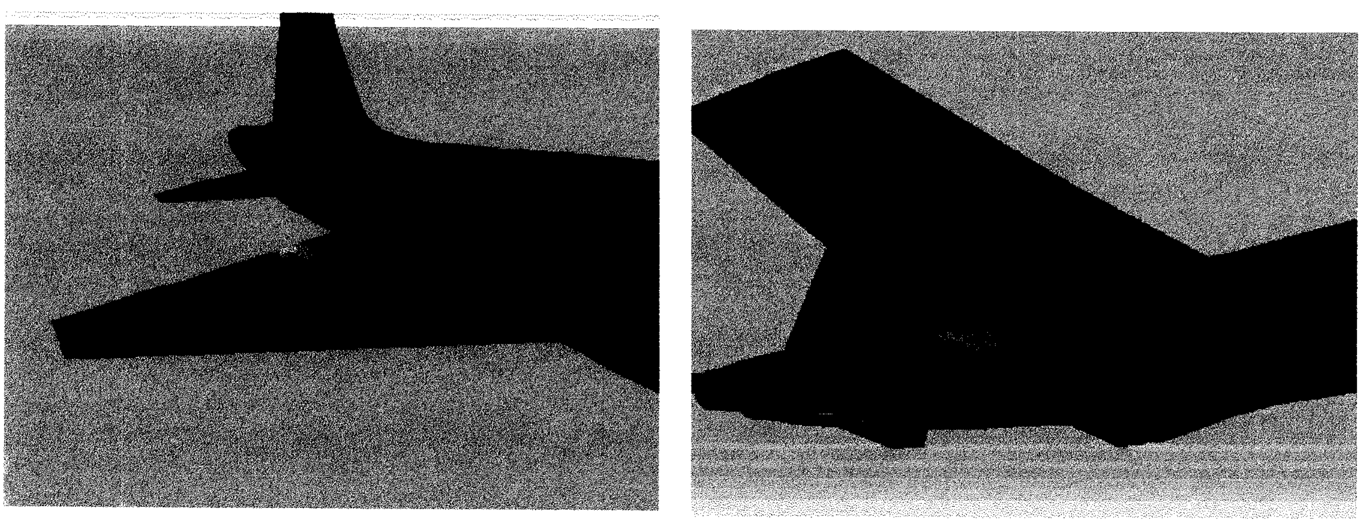


Figure 7. Note the difference in returns mapped to the top and the bottom of the T-38 model.

Another tool built into the 3D visualization software was the ability to "flag" the highest returns. The user can specify the number of flags. Figure 8 shows the eight highest returns for this configuration. The engine inlets were covered with RAM to eliminate their high return. Note the flags that appear "submerged" on the wing skin. These flags denote some of the highest return areas that were not mapped to the skin of the 3D CAD model, specifically the shrouded landing gear.

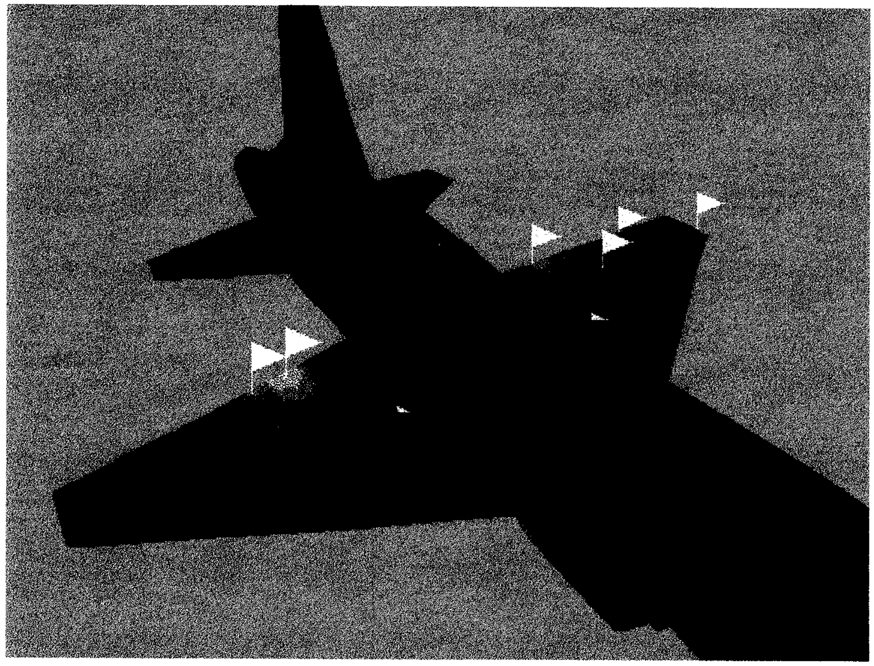


Figure 8. Flags can be depicted to show the location of the highest returns.

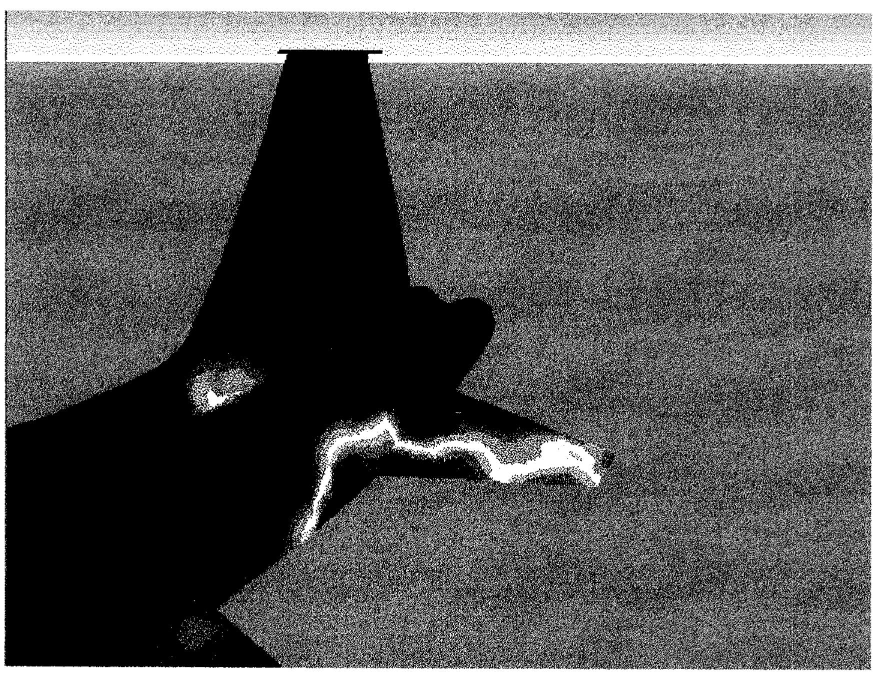


Figure 9. Multiple bounces of radar energy in the inlet causes the return to be mapped downrange.

Multi-bounce phenomena are a challenge when mapping returns to a 3D CAD model. Multi-bounce returns are delayed in time and therefore are mapped farther downrange than the point of the original return. The returns mapped on the tail surface of the T-38 in Figure 9, were caused by multiple bounces in the engine inlets. One way to depict this multi-bounce phenomenon is to provide a surface to map to, such as a horizontal plane that can be moved vertically.

In Figure 10, only returns that could not be mapped to the surface of the CAD model are displayed mapped to the horizontal plane as it moves vertically. The high return from the engine inlet cavity is displayed as bright colors aft of the aircraft fuselage. The high return also raises the noise floor, which results in the blue flash in front of the engine inlet.

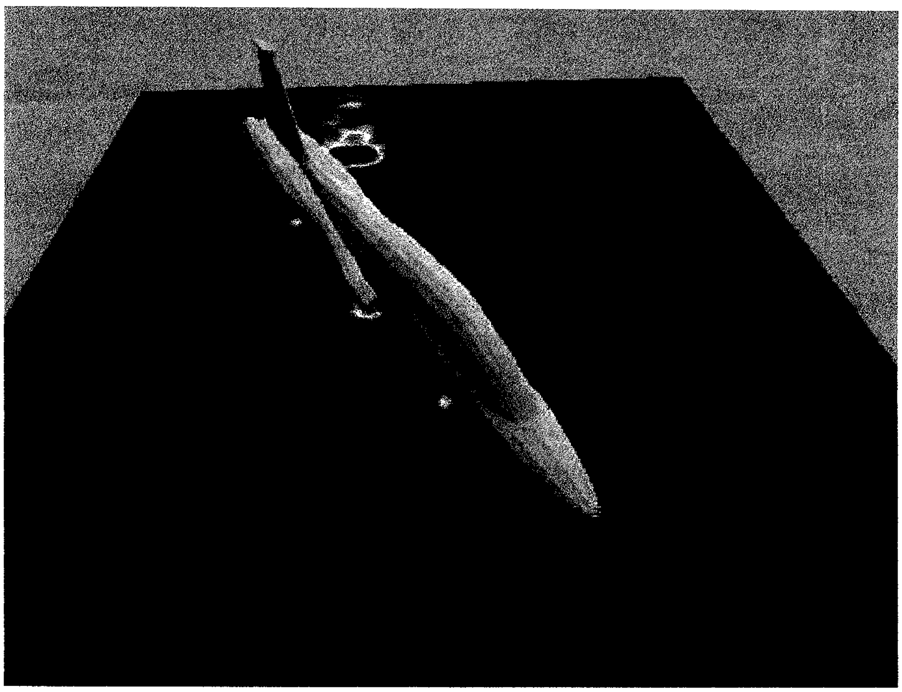


Figure 10. The horizontal plane provides a surface to map multiple-bounce radar returns that are delayed in time.

In conclusion, mapping radar returns to the surface of a 3D CAD model provides an intuitive way of visualizing the sources of radar returns. Since scanning the antenna in both vertical and horizontal dimensions collects three-dimensional data, the vertical ambiguity present in most traditional 2D images is eliminated. Specialized 3D software, developed by SCI for the Office of Naval Research, provides the link between 3D radar return data and commercial-off-the-shelf virtual reality software available to view CAD models. Multiple-bounce returns can be depicted using a moving plane to map returns delayed in time, and therefore outside of the CAD model surface.

Electronic Distribution of Technical Information via Satellite (EDTIS) Improved Access to Technical Information

By Steve Tomashefsky, Raytheon

Charles Satterthwaite, Air Force Research Laboratory

17 June 1999

ABSTRACT

The purpose of the Electronic Distribution of Technical Information via Satellite (EDTIS) is to link developing technologies to provide an increased capability for flight-line maintenance-crews and flight-crews. This capability is the greatly improved access to technical information at a greatly reduced cost. Enabling technologies are: the digitization and standardization of pertinent technical information and graphics; remote access of technical information over satellite networks; and the utilization of portable maintenance aids (PMA). The Advanced Avionics Multi-Radar Software Support System (AAMRSSS) performed a proof-of-concept, called the AC-130U System 2000 Demonstration Program, that digitized technical orders and accessed them via remote sites between Robins AFB, Georgia and Hurlburt Field, Florida. EDTIS will build upon this demonstration by providing highly desirable technical documentation to flight line repair crews for Special Operation Forces (SOF) Aircraft while providing the latest PMA interface to the satellite technical information links. This paper will review the AC-130U System 2000 Demonstration Program and provide an overview of the EDTIS program. The paper will also discuss some of the relevant technical advancements being taken advantage of to provide an EDTIS capability to SOF. The paper will conclude with a discussion of the potential savings of using these types of systems, and other technologies that might be leveraged to make it more potent.

INTRODUCTION

One of the major impacts of Acquisition Reform, is the necessity to reduce life cycle costs. The cost of maintenance is a significant factor in life cycle costs. Maintenance support of many weapon systems currently requires the printing and distribution of thousands of pages incorporated into the Technical Orders and their regular revisions in order to support the weapon system at various deployment sites. This effort is both cumbersome and costly and fails to provide current maintenance data in a timely manner. Maintenance delays are introduced as correct Technical Order information is sought. Incorrect maintenance actions are sometimes taken, resulting in “good” Line Replaceable Units (LRUs) being pulled, due to lack of correct repair information. The net result is a costly system, in need of a better way.

ANALYSIS OF THE PROBLEM

The rapid growth in complexity of weapon systems is straining the conventional methods of maintenance document generation, revision, and transmission to maintenance personnel. The existing system of paper documents has many inherent delays as a distribution system. These delays include the publishing, distribution, and warehousing of the documents. The use of change pages introduces another, expensive layer of labor intensive efforts. It is reported that the US Air Force system requires 14 months between the approval of document changes and their release to the maintenance personnel. In addition, the requirement to maintain and staff multiple libraries has a major cost impact.

A SOLUTION WITH MANY BENEFITS

Electronic document generation and distribution offers the opportunity to implement many worthwhile changes beyond simply increasing the speed of document distribution. A properly configured system can provide instantaneous release of an authorized document anywhere in the world. In addition, it gets the information to the user, the flight line maintenance technician.

But it can do much more. It can provide multiple levels of linked graphics and text to assist in understanding how to maintain unfamiliar equipment. It can prompt additional information to help probe in unfamiliar areas, and it can stand aside when available expertise is present. In order to realize the full advantage of electronic documents, an infrastructure must be installed which provides the required capability. Figure 1 diagrams the physical architecture of an electronic distribution network from a central (national) facility to one of N flight line maintenance stations.

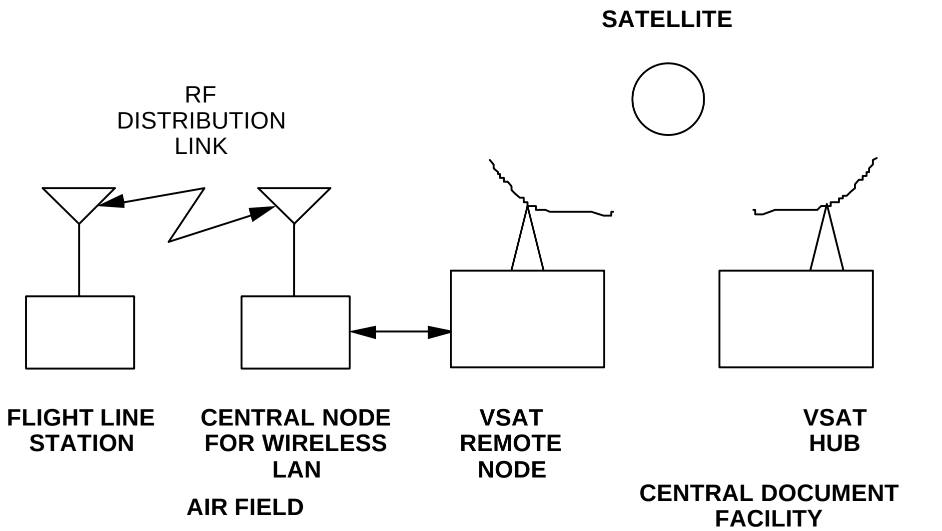


Figure 1

This network allows the transmission of data from the Very Small Aperture Terminal (VSAT) hub to the remote VSATs at very high rates to service multiple users. The VSAT remote node parses this high rate data stream and passes a relatively small amount of the data over the wireless LAN to the flight line stations. A flight line system with a wireless modem connection to a central data base storage system on the air field could be configured using a small commercial computer, such as a hand-held personal maintenance assistant (PMA) with cordless technology.

SYSTEM 2000 DEMONSTRATION PROGRAM

This effort demonstrated several necessary steps for achieving the goal of the elimination of the printing and distribution difficulties. These difficulties are associated with weapon system Technical Orders (TOs). This is accomplished through the paperless electronic delivery of these documents directly to the maintainer at any location on the globe equipped with a simple, inexpensive VSAT. The on-line distribution of maintenance related support data is a feature of the Raytheon System 2000 Precision Maintenance System.

In the System 2000 architecture, the documents are maintained in a central CONUS (Continental United States) repository and are delivered in the latest revision appropriate to the aircraft configuration specified by the maintainer. The electronic Technical Orders are in the form of Class IV Interactive Electronic Technical Manuals (IETMs) with electronic enhancements to greatly reduce the time required by the

maintainer in performing his function. The Technical Orders are delivered directly to the maintainer at the flight line via a small hand held wireless Portable Maintenance Aid linked directly to the local VSAT receiver/transmitter.

The initial phase of this project was sponsored by the Warner Robins Air Logistic Center (WR-ALC/LUE) and funded by USAF Productivity, Reliability, Availability and Maintainability (PRAM) Office of Wright-Patterson AFB (WPAFB). The project provided a demonstration of commercial satellite applicability in the Department of Defense environment for real-time on-line access and distribution of Technical Orders in IETM format to field users using transportable VSATs.

A VSAT Terminal and user PC console was installed at Hurlburt Field, as well as two loaned VSAT Terminals, one each to the second field site at Warner Robins ALC, Robins AFB, and the central data repository site at the Raytheon office. The equipment at each of the three sites was configured to meet the requirements of each site. A two-way communications link via contractor-operated satellite was also provided. When the satellite communications network was placed into service, the three sites were put into their "permanent" configuration, enabling communication among the sites. In establishing satellite network operation, many parameters were analyzed, such as projected bandwidth requirements, frequency availability, pointing angles, etc. The satellite network was then made available 24 hours per day, 7 days per week, on an as-desired basis, between the three sites noted above, for the designated period of performance.

A central repository of Electronic Technical Orders was established at the Raytheon Warner Robins office. Data installed at the central repository included a limited number of Technical Orders in IETM format for the AC-130U Gunship, as developed by the Technical and Management Services Corporation (TAMSCO) for the sponsor organization.

It was successfully demonstrated that IETMs could be transferred between locations via the satellite communications network. The System 2000 user interface provided the basic capability to access IETMs, initiate their transfer to and from the central database, and access the Advanced Integrated Maintenance Support System (AIMSS) tool to view and utilize the IETMs.

The IETMs selected for use in the demo were thought to be Class II, fully functioning, and complete. Unfortunately, several of the documents were actually supplements, and the main documents had to be retrieved. In addition, many of the diagrams included were not of the quality needed to be easily brought up to Class IV. Therefore, more work was required than anticipated, in converting the documents to Class IV. In retrospect, it may have been better to start with the paper documents, at least for consistency expectations. Once the IETMs were converted to Class IV, they functioned well as part of the System 2000 demonstration.

By using interactive, electronic documentation, the user is able to find the information needed quickly. Hot spots on the diagram link to sources detailed information, as seen in Figure 2.

The next snapshot (Figure 3) demonstrates how safety warnings have greater impact in interactive electronic documentation.

From the perspective of the IETM user, there were not enough IETMs provided to allow them to evaluate the quality of the IETMs themselves. Although the main concept of the demo was to demonstrate IETM distribution via the satellite network, it is important to provide enough data samples to all of the users throughout the demonstration system to facilitate a system-wide evaluation. The user community has identified several IETMs, and these are being retrieved. They are in paper format. This will provide a good indication of the end-to-end processing needed to replace existing paper Technical Orders with Class IV/V IETMs.

This task demonstrated many aspects of how the System 2000 Precision Maintenance System is a viable and practical approach to the urgent need to reduce the cost of Operations and Maintenance of USAF aircraft.

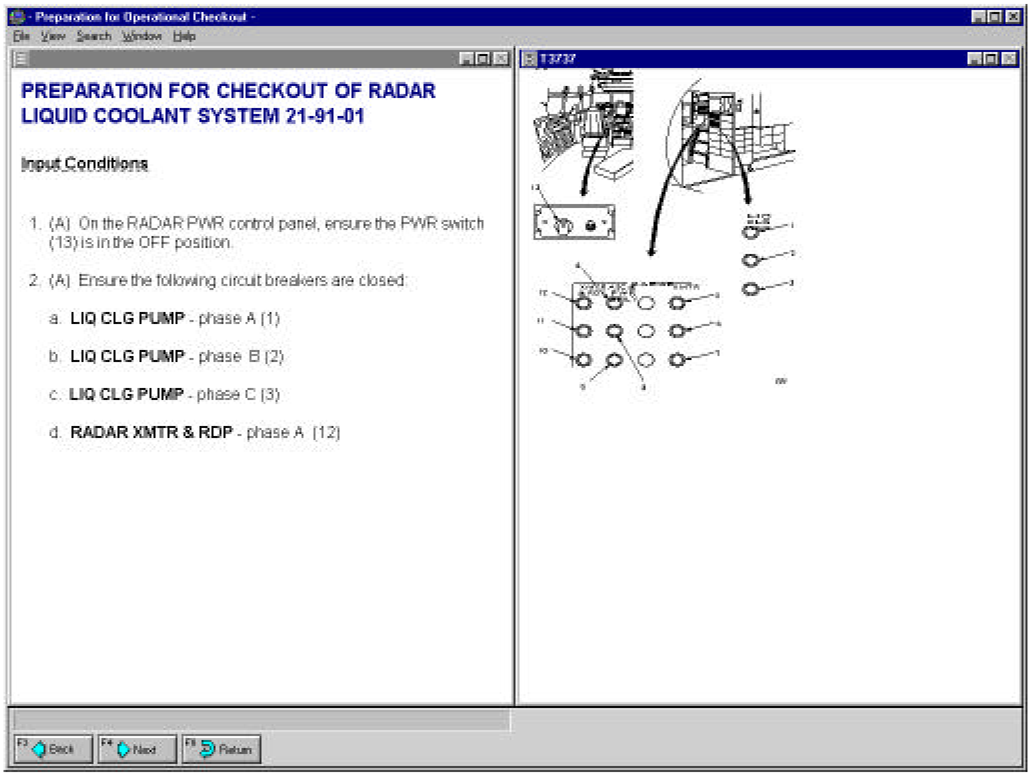


Figure 2

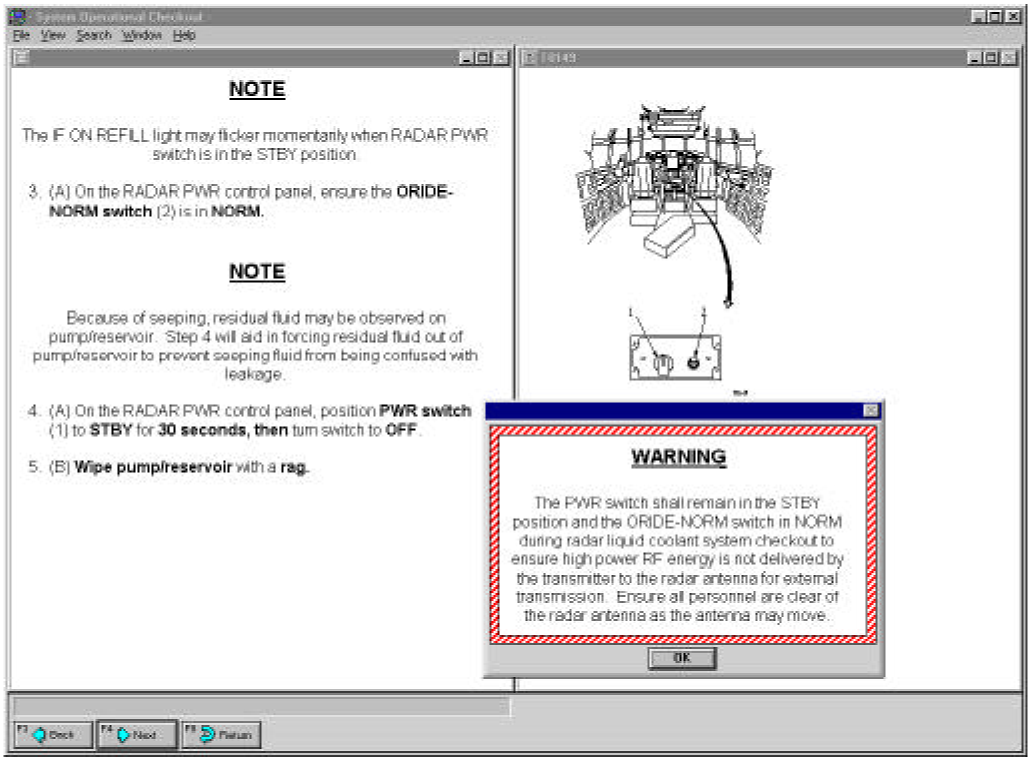


Figure 3

AN OVERVIEW OF EDTIS

One of the significant benefits of the System 2000 Precision Maintenance System is its ability to adapt to the requirements of each user community, while maintaining its predominantly Commercial-Off-The-Shelf (COTS) architecture. Requirements for each deployment vary due to a variety of reasons, including:

- Physical architecture of the user community, such as the number and location of sites, both local and remote,
- Amount of technical information to be accommodated by the system,
- Frequency of information updates, and
- Security requirements.

EDTIS, as well as its predecessor AAMRSSS, performed an analysis of the current process of deploying, referencing, and maintaining Technical Orders of Special Operations Forces (SOF) Aircraft at Hurlburt Field, and prepared an initial System 2000 architecture definition based on the needs of the user. This architecture was implemented on a small scale, allowing user feedback to determine how well the initial design performs, as well as areas that need improvement or adjustments.

It is important to note that while the initial implementation of an electronic information distribution system is thought of in terms of improving the infrastructure of the current process, the implementation actually allows processes to be redesigned from the ground up. Hence, the analysis of an installation should have two distinct facets:

1. A comparison of the current process using the new infrastructure vs. the existing infrastructure,
2. A complete re-evaluation of the current process, to seek ways that the new infrastructure could support elimination of costly and outdated portions of the process.

The first is an evaluation of the evolutionary merits of the new system. This is critical, because it is not reasonable to expect that a process in day-to-day use can be replaced with a radically new process overnight, regardless of how well it performs. The second is also critical, though more difficult to accomplish. By thinking out-of-the-box, real and substantial cost savings can be achieved. This longer-term vision needs to be well coordinated to minimize disruption to the users.

As such, EDTIS focuses on two key areas:

- Technical Documentation Usability
- Technical Documentation Accessibility

In keeping with the objectives of the EDTIS program, the technical documentation studied refers to paper TOs and electronic IETMs, although much of the results of the EDTIS program can be applied to countless types of information, from software documentation to logistics data.

EDTIS TECHNICAL DOCUMENTATION USABILITY

IETMs have many advantages over paper TOs. As a replacement for TOs, they minimize or completely eliminate the problems associated with the printing, shipping, storage, and deterioration of paper. Even more significant are the additional benefits not possible with paper. These include the capability to support:

- Interactive use, which guides the user through maintenance procedures
- Adapt procedures in real time according to current fault indications
- Maintain test procedure variations according to the configuration of the System-Under-Test
- Inclusion of user notes and comments into procedures
- Capture of information produced during maintenance actions

- Self-learning, based on knowledge base built from data capture
- Adaptive training based on actual procedures, and suited for Just-In-Time and distance training

However, for users that are accustomed to working with paper, not having a physical document may be awkward for a period of time. The system implementation must account for this, and must have enough “redeeming qualities” to encourage the user to get beyond this stage.

EDTIS TECHNICAL DOCUMENTATION ACCESSIBILITY

DIGITIZATION OF TECHNICAL INFORMATION

The EDTIS program examines the content of several Technical Orders used in the maintenance of various USAF systems. The TOs, which contain step-by-step maintenance procedures, diagrams, and background information, are structured as a compromise between the way they are expected to be used, and the reality of being published in a paper document format, namely a series of sequential pages, bound together.

It is inevitable that many procedures will have several alternative variations. Such variations come about from maintaining similar, but not identical aircraft; different revisions of hardware and software of the system being maintained; and a host of other reasons. In this scenario, variations to fundamental procedures are awkward to script into a paper document. The result is that each variation of the basic procedure is reproduced in the text repeatedly, or a core procedure is presented, with annotations identifying the steps involved that "tailor" the procedure to the user's particular situation. The first alternative generates large documents that are difficult to maintain, since complex procedures are nearly duplicated throughout the document. The second puts the burden on the user to correctly execute the procedure while minding the annotations to be sure that each step of the procedure is the correct one for his/her configuration.

In preparing to create an electronic document (IETM), it is important to take advantage of the ability for the document to contain information that enables the document viewer to adapt the presentation to the user according to the particular situation. For example, the procedure would initially query the user to the configuration of the hardware and software. Subsequent maintenance steps would be presented to the user only if applicable to the user's system configuration.

Since IETMs are interactive, they can guide the user through the repair process. They can, depending on the effort committed to their authoring, automatically identify the precise repair procedure indicated by the system's symptoms and/or diagnosed faults. They can display the correct, pertinent diagrams and schematics, as well as parts and interchangeability listings. Eliminated is the need to manually search through volumes of paper documents or CD-ROMs, which are often outdated, lost, or damaged. IETMs can harness the power of self-learning. IETMs constructed in this way capture data from each maintenance action, continuously building a knowledge base that becomes smarter with each use.

This is one example of the power of electronic documentation. Other areas made possible include:

- Adaptive training, where the procedures are used for training purposes, and are able to adapt to the particular training situation, and even "learn" what areas trainees have the most success and the most trouble with, to help improve the training for the next student.

- The diagnostic procedures can be enhanced to do much more without causing additional burden on the user, since much more logic can be included "behind the scenes" of the presentation of the procedure to the user. Additional logic can make use of historical maintenance and failure data, calibration results, schematic analysis, etc.

REMOTE ACCESS THROUGH SATELLITE

The use of satellite technology to provide the infrastructure to use electronic documents provides significant capability, several of which are not available through other means, including:

- Virtually instantaneous worldwide data delivery and collection
- Assessment of system damage incurred during battle
- Visibility into asset management and system configurations
- Integration of remote sites into a cohesive system
- Databases kept current and available
- Central configuration management

PORTABLE MAINTENANCE AIDS

In order to receive the benefits of electronic documents, they must be viewed on some form of an electronic display. For the aircraft maintainer, a Portable Maintenance Aide (PMA) is used. The PMA is linked to a local server, either by radio link or through a disk-docking system. The particulars of each installation determine which method of linking is used. The PMA can also be designed with the capability of interfacing with a bus of the system under test for even more powerful diagnostic capability.

EDTIS will analyze various commercially available devices for suitability. Several ruggidized laptop computers will be evaluated for various features, including screen size and quality, reaction to heat, cold, and sunlight, battery life, processing power, cost, and other features important to users.

POTENTIAL SAVINGS OF EDTIS

It is evident that the technology demonstrated by the AAMRSSS and EDTIS programs can make a significant impact to the way that aircraft maintenance is performed. Some of the changes are so significant that it is difficult to quantify without application to a particular implementation. That is, any organization that implements the technology presented here will adapt their implementation according to their requirements. The individual installations will vary widely, as will the cost savings. The AAMRSSS and EDTIS demonstrations provide proof of concept and the collection of user feedback for design improvements, and include qualitative considerations for cost savings. As the technology is implemented in a variety of situations, data will become available indicating expected savings.

It is safe to say that the cost of incorrect maintenance actions due to outdated materials or misunderstood configuration-dependent procedures can be tremendous, even life threatening. It is from this perspective that the above programs have focused on the technical aspects, since, virtually by definition, if the technology can reduce incorrect maintenance actions, the savings will be significant and worthwhile.

SUMMARY AND CONCLUSIONS

The following is a list of several advantages of an EDTIS system:

- Eliminate distribution of paper Technical Orders and associated configuration management costs
- Eliminate distribution delays
- Assuring availability of the most current technical data
- Eliminate lost TOs and change pages

- Enable rapid deployment of Aircraft support infrastructure
- Eliminate hundreds of pounds (conservative figure) of paper
- Increase aircraft payload
- Reduced Mean Time To Repair via improved data accuracy
- Increase combat capability by reducing aircraft down time
- Decrease repair cycle costs by reducing false LRU pulls
- Reduce spares requirement by reducing false pulls
- Reduced manpower skill level requirements via "smart" IETMs
- New capabilities possible – maintenance history, fault diagnosis, automated parts ordering, etc.
- Commercial Satellite redundancy reduces resource dependence vulnerability
- On-line Expert assistance feasible to enhance 2-level maintenance policy

The best summary of this paper is to contrast the above list with common situations that weapon system maintainers face:

- Dependency on distribution of paper Technical Orders from multiple sources with non-standard configuration management of each source
- Frequent distribution delays
- Non-availability of the most current technical data
- Lost TOs and change pages, hard copies deteriorate after repeated usage
- Delayed deployment of Aircraft support infrastructure
- Required to handle and move hundreds of pounds (conservative figure) of paper
- Decreased aircraft payload
- Mean Time To Repair increased
- Decreased combat capability due to increased aircraft down time
- Increased repair cycle costs because of increased false LRU pulls
- More spares requirement because increased false pulls
- Higher manpower skill level requirements because of untimely technical data
- Reduced access to new capabilities, because of the non-standard distribution of technical data
- Inherent resource dependence vulnerability
- On-line Expert assistance difficult to enhance

In conclusion, the work performed by System 2000, AAMRSSS, and EDTIS supports a common sense approach that weapon system crew chiefs historically stated, defined, and designed. These crew chiefs intimate knowledge of their weapon systems and the processes that maintain them give rich insight into the hidden costs of the system life-cycle, those of operation and maintenance.

A key resource required for operational and maintenance support is the timely access of accurate technical documentation. The EDTIS program not only provides this useful technical information; it also enables addition of information technologies.

References

(1) Tomashefsky, Steve, AC130U System 2000 Demonstration Program from Delivery Order 0007 of Contract F33615-92-D-1050, Final Report, June 1998.

(2) Satterthwaite, C.P., The Maintenance of Operational Flight Programs, DASC, Oct. 1992.

(3) Miyahara, G., Satterthwaite, C.P., The Software Development Facility as A Multi-Platform Support Environment, International Test and Evaluation Association Symposium, 14-18 October 1996.

(4) Miyahara, G., Satterthwaite, C.P., A Multi-Platform Support Environment, Co-authored with NAECON 97, July 1997.

(5) Miyahara, G., Satterthwaite, C.P., Tomashefsky, S., Harnage, I., A Comparison Of Fly-Fix-Fly Testing To The Software Development Facility Testing Approach, DASC, Oct. 1997.

Electronic Distribution of Technical Information via Satellite (EDTIS) Improved Access to Technical Information

•Charles Satterthwaite: AFRL/IFTA

•Steve Tomashefsky: Raytheon

17 June 1999
JAWSSS 99

Embedded Information System Re-engineering (EISR)

BASELINE

- Multiple Weapon Systems
- Domain Expertise
- Recent Upgrade Technology Study Results

Leverage Commercial Technology

Automatic Language Translation

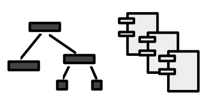
- Ada 83 to Ada 95
- CMS-2 to Ada
- Jovial to Ada
- FORTRAN to Ada

ASSESSMENT

Current Capability Vs. Need

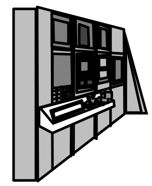
DEVELOPMENT

Mature JOVIAL J73 to C Re-engineering Capability



VALIDATION

F-16 DE/CIS & FCC Software Test Cases



Option for Demo of Execution in Hotbench Facility

TRANSITION

Technical

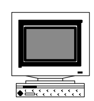
F16 CCIP M3++

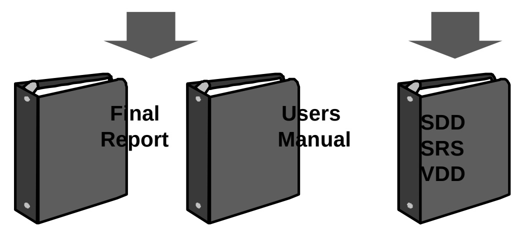
Commercial

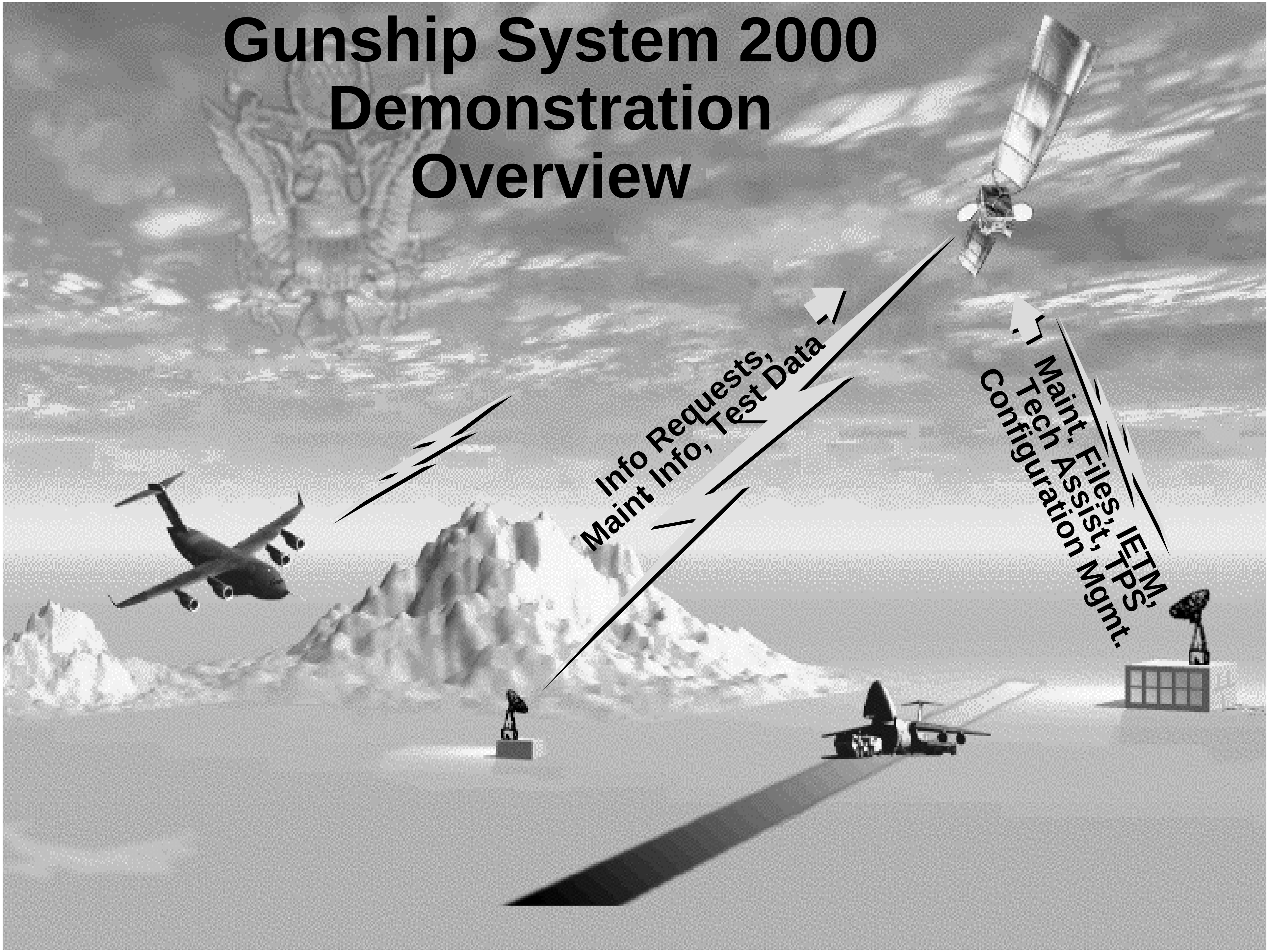
DEMONSTRATIONS & DELIVERABLES

EISR SYSTEM

- ***Nominal***
- ***Mature***
- ***Final***






Gunship System 2000
Demonstration
Overview
Info Requests,
Maint Info, Test Data
Maint. Files, IETM,
Tech Assist, TPS,
Configuration Mgmt.

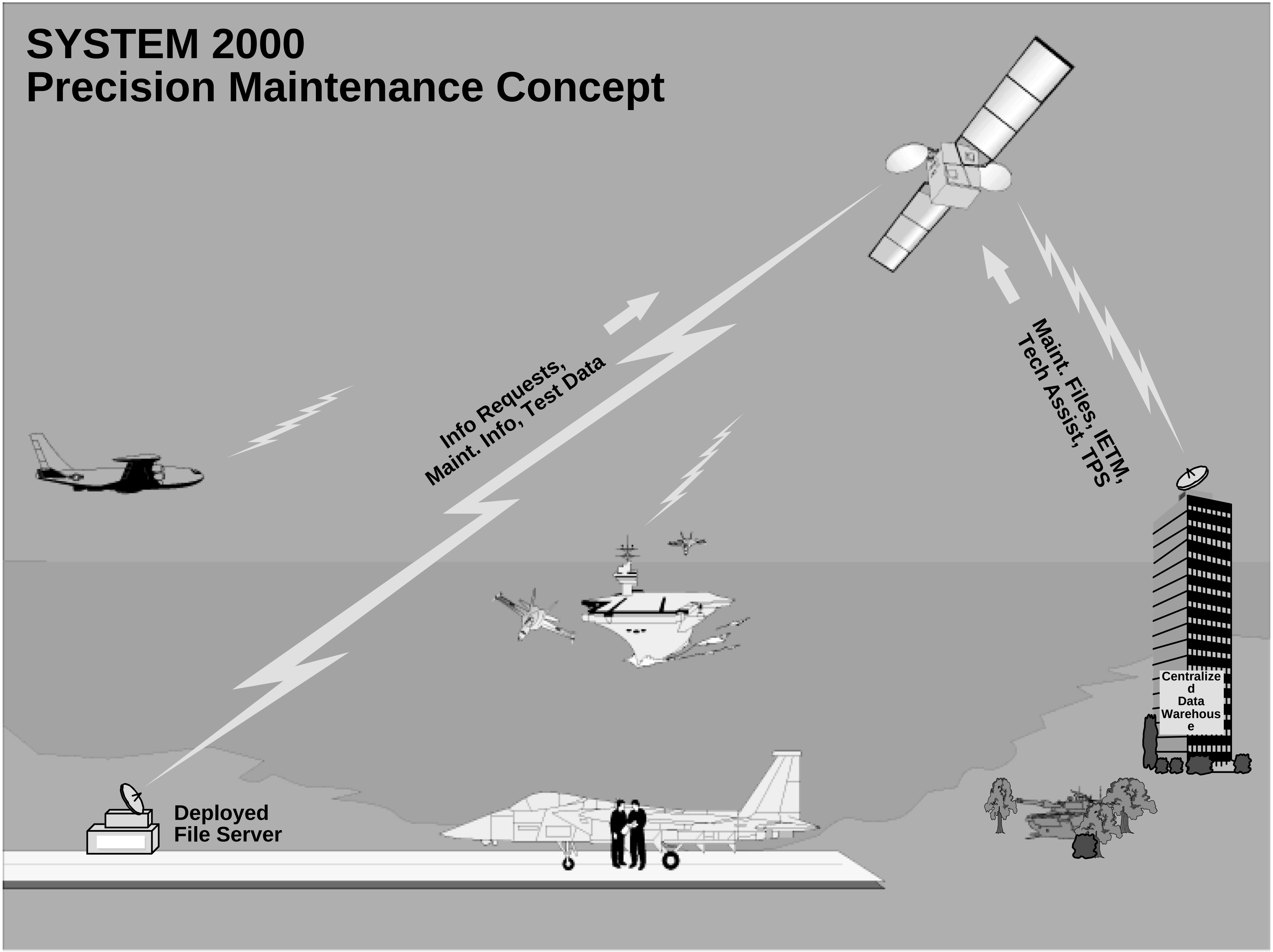
Project Team

Program Management
Allison Heaton
Joel Moorvitch
Robert Rassa
Steve Tomashefsky

IETM Engineering
Colleen Wooley

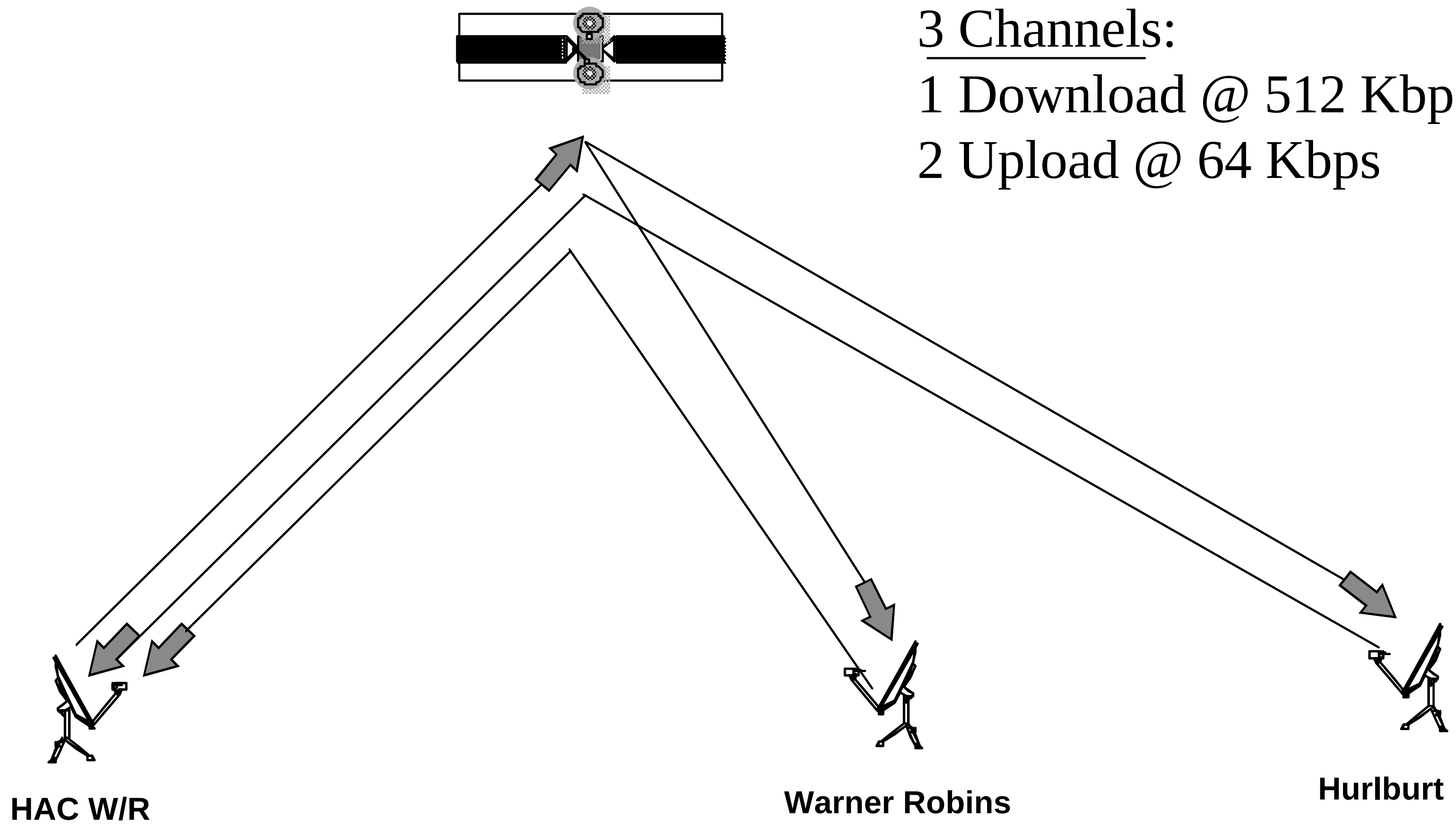
System Engineering
Maceo Foster
Philip Gore
Roy Nesson
Doug Specking
Walt Yogi

AIMSS
Tim Gohranson
Robert Schwarzberg

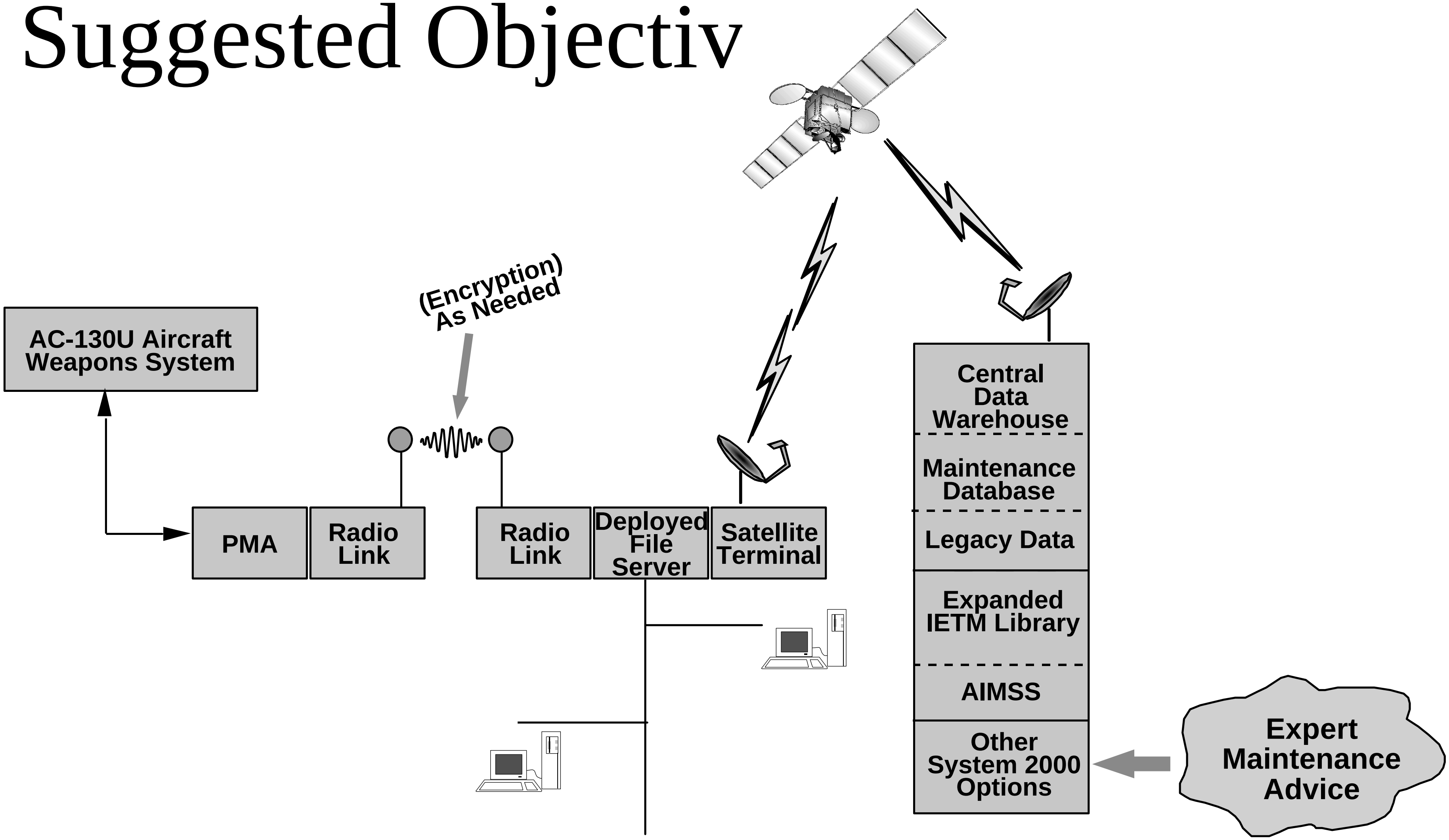

SYSTEM 2000
Precision Maintenance Concept
Info Requests,
Maint. Info, Test Data
Maint. Files, IETM,
Tech Assist, TPS
Centralize
d
Data
Warehous
e
Deployed
File Server

System 2000 Gunship Demo
Phase 1 Architecture

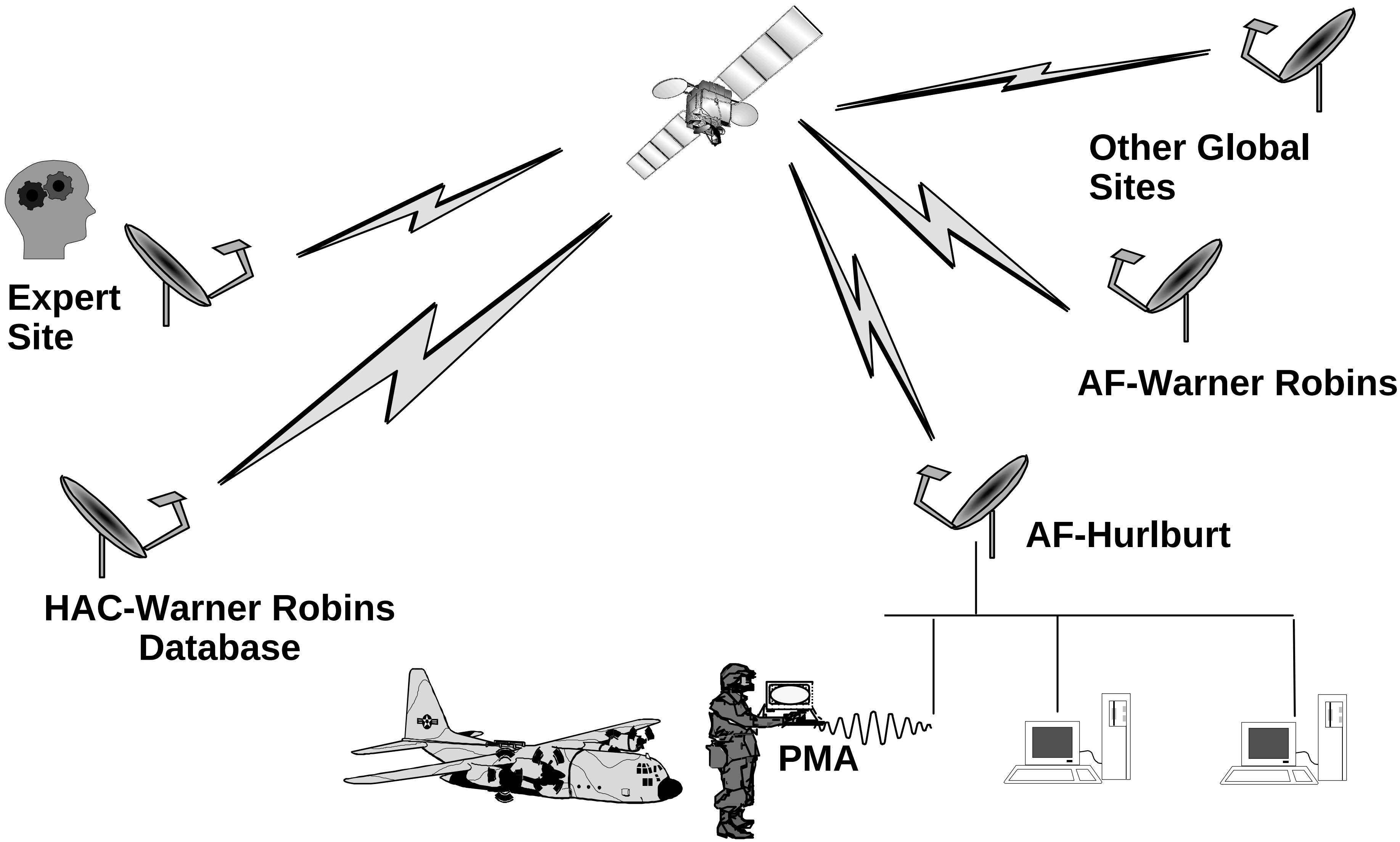
3 Channels:
1 Download @ 512 Kbps
2 Upload @ 64 Kbps



System 2000 Phase 2 Suggested Objectiv



System 2000 Gunship Phase 2 Architecture



The following is a list of several advantages of an EDTIS system:

- Eliminate distribution of paper Technical Orders and associated configuration management costs
- Eliminate distribution delays
- Assuring availability of the most current technical data
- Eliminate lost TOs and change pages
- Enable rapid deployment of Aircraft support infrastructure
- Eliminate hundreds of pounds (conservative figure) of paper
- Increase aircraft payload
- Reduced Mean Time To Repair via improved data accuracy
- Increase combat capability by reducing aircraft down time
- Decrease repair cycle costs by reducing false LRU pulls
- Reduce spares requirement by reducing false pulls
- Reduced manpower skill level requirements via “smart” IETMs
- New capabilities possible – maintenance history, fault diagnosis, automated parts ordering, etc.
- Commercial Satellite redundancy reduces resource dependence vulnerability
- On-line Expert assistance feasible to enhance 2-level maintenance policy

The best summary of this paper is to contrast the above list with common situations that weapon system maintainers face:

- Dependency on distribution of paper Technical Orders from multiple sources with non-standard configuration management of each source
- Frequent distribution delays
- Non-availability of the most current technical data
- Lost TOs and change pages, hard copies deteriorate after repeated usage
- Delayed deployment of Aircraft support infrastructure
- Required to handle and move hundreds of pounds (conservative figure) of paper
- Decreased aircraft payload
- Mean Time To Repair increased
- Decreased combat capability due to increased aircraft down time
- Increased repair cycle costs because of increased false LRU pulls
- More spares requirement because increased false pulls
- Higher manpower skill level requirements because of untimely technical data
- Reduced access to new capabilities, because of the non-standard distribution of technical data
- Inherent resource dependence vulnerability
- On-line Expert assistance difficult to enhance

SMOKE AND OBSCURANT MODELING IN SUPPORT OF SIMULATION BASED ACQUISITION AND TRAINING

David J. Johnston
Bruce W. Fischer
OptiMetrics, Inc.
Forest Hill, Maryland 21050
Telephone: (410) 893-9714
Telefax: (410) 893-9717
E-Mail: johnston@omi.com

William G. Rouse
U.S. Army Edgewood Chemical Biological Center
AMSSB-RRT-PA
Aberdeen Proving Ground, Maryland 21010
Telephone: (410) 436-1848
Telefax: (410) 436-2998
E-Mail: wgrouse@sbccom.apgea.army.mil

ABSTRACT

The U.S. Army Edgewood Chemical Biological Center (ECBC) and its parent command are committed to the implementation of simulation-based acquisition and training techniques. Their value has been demonstrated repeatedly by many organizations and in countless situations representing all aspects of the product life cycle, including combat development, material development, manufacturing, training, and employment. Models and simulations have become practical tools that routinely replace laboratory experiments, field activities, and training exercises while reducing cost and improving safety. They could be particularly effective for smoke and obscurant scenarios, which carry significant environmental clearance costs and additional safety considerations. Numerous models have been developed to simulate smoke and obscurant systems, but most of these have focused on detailed scientific and engineering issues, such as cloud physics and electro-optical performance. Although several attempts have been made to integrate these models into constructive and distributed interactive simulations, no smoke and obscurant model has emerged that supports opertational level activities. This is a significant shortcoming that hampers both training and acquisition. This paper reviews the state of smoke and obscurant models and illustrates how existing simulations have been used to support acquisition and training. It also identifies requirements for operational-level tools and establish a framework for their development.

1. MODELING AND SIMULATION TRENDS

Modeling and simulation (M&S) has become an essential technology that is influencing a growing number of mission-critical activities. Organizations within DoD are increasingly using it for operational planning; research, development, and acquisition; test and evaluation; training and mission rehearsal; and, doctrine development. This growth is being fueled by budgetary constraints, environmental concerns, and technological advances, which reduce the cost of complex computer systems while increasing their capabilities.

Historically, most M&S activities have been conducted in vertical stovepipes within application domains (figure 1) and there has been little horizontal integration. The constructive wargames and virtual simulations used for training have seldom been linked, for example, to engineering-level simulations or the physical models they use.

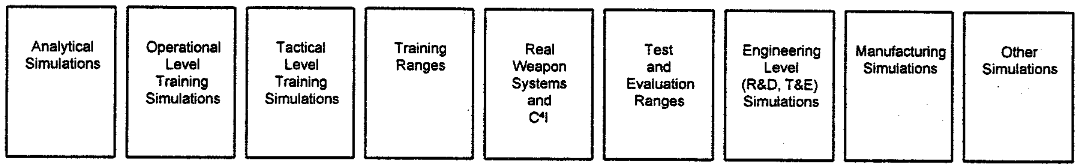


Figure 1. DoD modeling and simulation domains.

The computational burden imposed by high fidelity models has often limited their utility beyond the application domain for which they were developed. This is certainly true for smoke and obscurant models, which have little presence in the preeminent simulation environments. Until recently, horizontal integration was infeasible due to limitations imposed by hardware, software, and design methodologies. This situation is changing, however, as technological developments increase computer system performance, simplify connectivity, reduce cost, improve usability, enhance the development process, and promote software reuse. These factors are reshaping the nature of DoD models and driving a paradigm shift toward a more flexible and efficient simulation environment (figure 2).

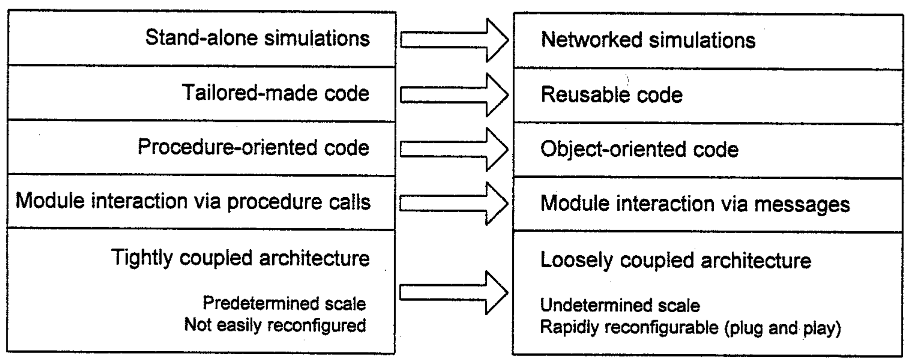


Figure 2. Modeling and simulation trends.

The Defense Modeling and Simulation Office (DMSO) has capitalized on these trends to produce a High Level Architecture (HLA)[1] that unifies all M&S domains under a single technical framework. Future DoD M&S systems will be required to comply with the HLA, which specifies a design philosophy, imposes documentation requirements, and provides a common cross-platform run time infrastructure (RTI). The HLA will facilitate linkages between models and promote software reuse across all M&S domains. We are entering a period where software, that was developed for one specific purpose, can be used without modification in many different applications. This will enable engineering-level, constructive wargames, and virtual simulations to use physical models to increase their fidelity with real world phenomena.

2. SMOKE AND OBSCURANT MODELS

Several physical models have been developed to simulate the production, transport, and diffusion of battlefield obscurants and assess their effect on tactical sensors. The U.S. Army Research Laboratory (ARL) has been a major contributor and it maintains two smoke and obscurant models in its Electro-Optical Systems Atmospheric Effects Library[2,3]. GRNADE[4] simulates multiple-round salvos of tube-launched grenades (L8A1 and M76) and is used for

self-screening analysis. The Combined Obscuration Model for Battlefield-Induced Contaminants (COMBIC)[5,6] is more comprehensive and can simulate: high explosive and vehicular dust; phosphorus and hexachloroethane munitions; diesel fuel, oil, and rubber fires; generator-disseminated oils; other screening aerosols, and user-defined sources.

COMBIC has been used in numerous, diverse applications and is arguably the dominant model in this field. It operates on level terrain and only considers a horizontally homogeneous wind (figure 3). These limitations led ARL to develop a derivative model, the Simulation of Aerosol Behavior in Realistic Environments (SABRE)[7], that can use a terrain-dependent wind field. SABRE was an EOSAEL module for some time, but is no longer supported by ARL and has been withdrawn from the library, leaving it without a smoke and obscurant model that handles non-uniform wind and terrain.

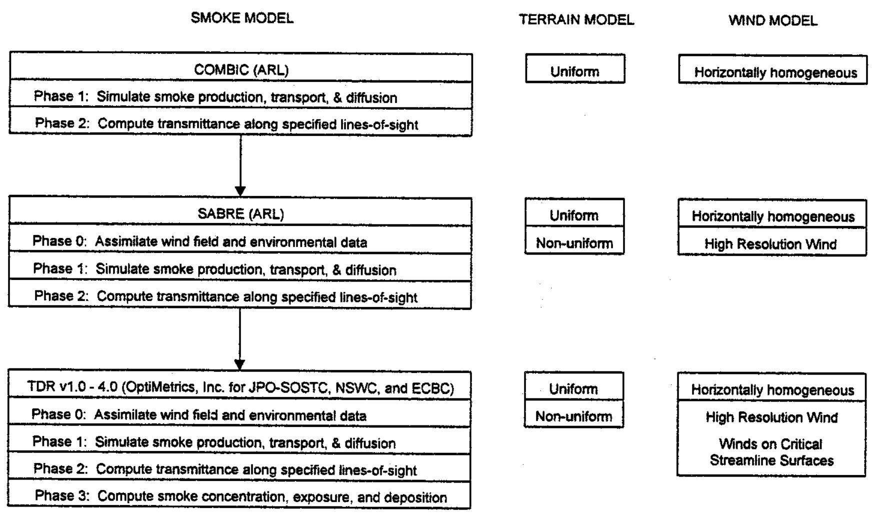


Figure 3. Lineage and primary characteristics of COMBIC and its derivatives.

The Joint Project Office for Smoke, Obscurants, and Special Technologies Counter-measures (JPO-SOSTC), Naval Surface Warfare Center (NSWC), ECBC, and OptiMetrics, Inc. (OMI) have enhanced SABRE to create the Transport, Diffusion, and Radiance (TDR) model[8]. It has been integrated into several applications and can operate in a stand-alone mode on numerous computing platforms.

COMBIC and TDR were originally developed in the mid 1980s to the early 1990s using prevailing techniques. They are large, monolithic programs that are written in FORTRAN using extremely unstructured code. Their software components make extensive use of global variables and are, therefore, highly interdependent. In short, they are not well suited for use in a simulation environment that is increasingly distributed and object-oriented.

Both models describe clouds as a collection of one to five subclouds, which can be either Gaussian puffs or plumes. When a source is activated, subcloud states are computed at discrete downwind distances and the results are saved in a history file. All predictions are made using the atmospheric conditions that existed at the time of source activation. Although this approach is computationally efficient, it is not responsive to changes in atmospheric conditions that might occur during the cloud's lifetime. It also requires a large amount of data to be maintained (and possibly transferred) for subsequent calculations.

Because they were developed several years ago, COMBIC and TDR only simulate sources and obscurants that were available (primarily to U.S. forces) at that time. The models have not been updated significantly to include equipment, munitions, or materials that have been fielded in recent years or are currently under development by the U.S., our allies, and potential adversaries. Both models enable the user to specify source and obscurant characteristics through data inputs, but this requires an intimate knowledge of the material and model properties.

Neither of these programs model vehicles or vehicular components. They have no awareness of specific vehicle types nor the location and orientation of smoke generation equipment on those vehicles. Consequently, COMBIC and TDR could not be used by themselves to examine operational usage where component placement is an issue. This limitation is aggravated by their inability to accept unscripted inputs. The models cannot be used without augmentation to respond to ad hoc smoke events that might be generated randomly, by a constructive wargame under player control, or by networked simulators in a virtual exercise. In addition some deficiencies have been noted in their predictive algorithms. Most notably, COMBIC does not accurately model evaporative losses from disseminated oils as a function of temperature[9]. This affects the predicted quantity of suspended liquid that is actually available for producing screening effects, a critical factor in some applications where oil smokes are employed.

3. SMOKE SYSTEM PERFORMANCE MODEL

The Smoke System Performance Model (SSPM)[10] was developed by ECBC and OMI to eliminate many of the limitations noted above. It is a collection of C++ classes that model the essential elements of smoke and obscurant systems. The classes can be integrated with engineering-level models, constructive wargames, and virtual simulations to enhance their ability to simulate battlefield obscuration.

SSPM models relevant items, such as vehicles, components, clouds, obscurant materials, and vehicular grenades. Each class encapsulates the essential technical characteristics of the item it represents, as they relate to smoke and obscurant production, and provides default functionality. The default behaviors vary in sophistication and can be overridden if enhanced functionality is required. The notional default behavior of SSPM clouds can be enhanced by using a smoke and obscurant model, such as COMBIC or TDR, to simulate cloud production, transport, and diffusion. When this is done, SSPM acts as a preprocessor by simulating operations at a higher level and directing the smoke and obscurant models to place clouds with specified characteristics at designated times and places.

SSPM is limited only by the scope of the systems it currently models. The latest version can simulate thirteen vehicles, seven vehicle-launched grenades, vehicle engine exhaust smoke systems, and two smoke generators. It does not yet model smoke pots or artillery, mortar, rocket, and aircraft-delivered obscurants. Only one of the vehicles and one of the grenades are foreign systems.

4. ENGINEERING LEVEL MODELS

SSPM has been linked to COMBIC in the Cloud Density Visualization Utility (CDVis)[10], an engineering-level model that presents a graphical representation of simulated clouds (figure 4). CDVis uses SSPM to execute complex obscuration scenarios, COMBIC Phase I to predict cloud histories, and COMBIC Phase II to compute concentration path lengths along specified lines-of-sight. The concentration path lengths or their corresponding transmittance values are then presented as false color images, enabling the user to perceive the clouds in three dimensions as a function of time.

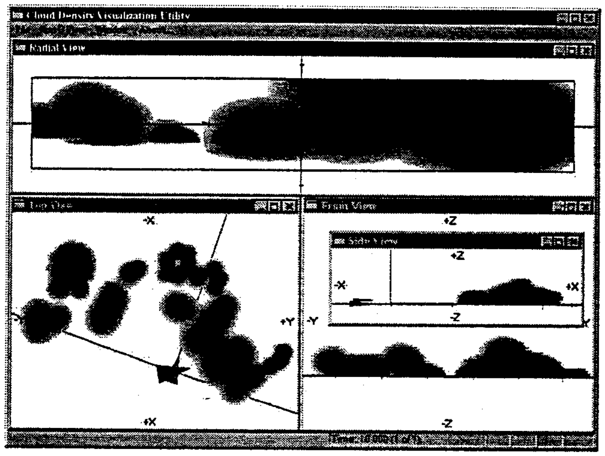


Figure 4. CDVis displaying cloud density images for the front, side, top, and radial views of a simulated obscuration event.

SSPM has also been linked to COMBIC in a battle management system (BMS) for chemical staff officers that will be used to evaluate smoke and obscurant plans (figure 5). The BMS is similar to CDVis in its use of SSPM and COMBIC, but it superimposes a birds eye view of the simulated clouds on a tactical land map. The BMS also predicts sensor effectiveness on a horizontal plane from a given location at a designated time and distance above ground level. Effectiveness is presented as a radar plot that uses green, amber, and red to depict regions of increasing cloud density in accordance with specified transmission thresholds.

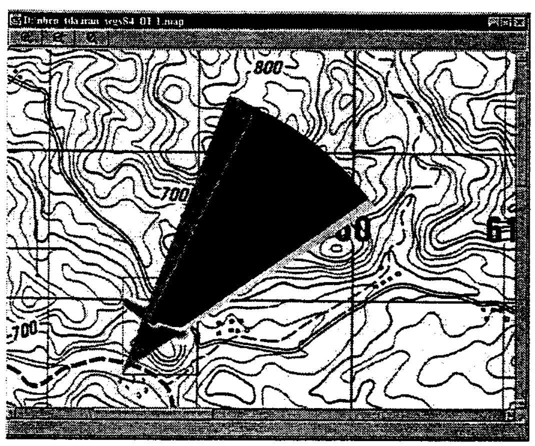


Figure 5. Chemical Staff Officer's BMS displaying a sensor effectiveness plot superimposed on a cloud density image of a simulated obscuration event.

This program demonstrates the power of object-oriented methodologies, which foster software reuse by encapsulating functionality and enabling components to be assembled into new and different applications. Most of the smoke-related code in BMS is identical to that used in CDVis. The only difference is some minor additions that were applied to support its unique display requirements. Also, the BMS graphical user interface is written in Java while SSPM and its CDVis extensions are written in C++ and the extended cloud class places an object wrapper around COMBIC's FORTRAN code. The object-oriented technology enables these disparate components to be drawn together with relative ease to create a new and useful application.

5. CONSTRUCTIVE WARGAMES

JPO-SOSTC, NSWC, the USMC Systems Command, and OMI have integrated TDR into a many-on-many Sensor/Obscurant Engagement Simulation (SOES). It has been used by combat and material developers to assess tactical concepts for smoke employment in littoral operations (figure 6). SOES uses physical models to simulate sensor performance and TDR Phase I to produce terrain-sensitive smoke clouds. Intervisibility issues are addressed using digital terrain elevation data and TDR Phase II.

SOES uses TDR as an independent executable program without augmentation, so it is limited to the smoke sources that TDR inherently supports. These sources are positioned and activated in accordance with an scripted scenario.

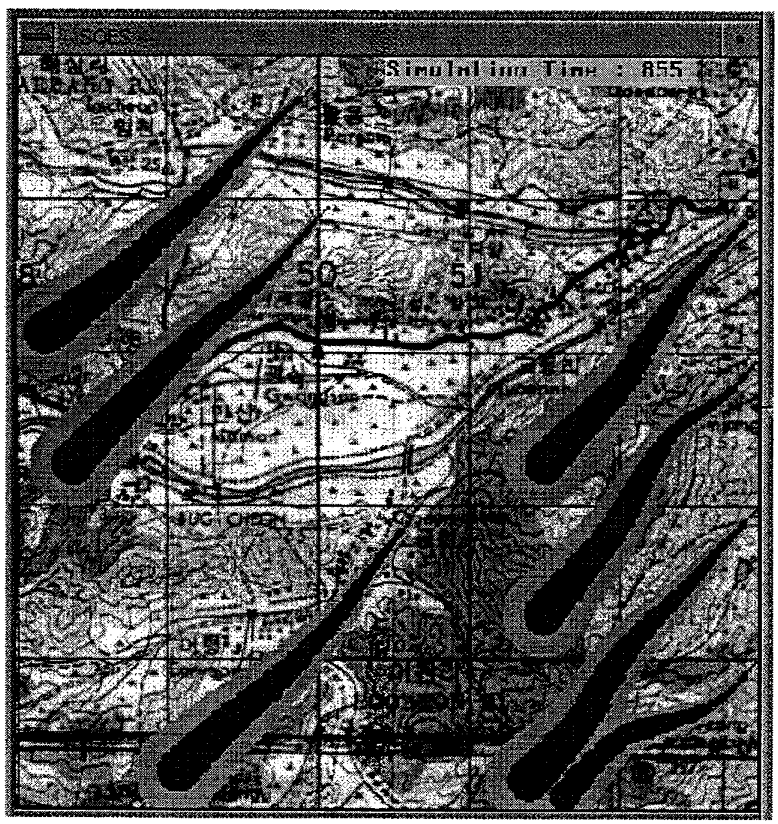


Figure 6. A SOES display depicting terrain sensitive TDR-generated clouds.

The US Army Training and Doctrine Command has integrated COMBIC into CASTFOREM, a stochastic force-on-force model that is used to assess combat system performance[11]. It is the Army's primary tool for conducting formal Analysis of Alternatives (AoA). CASTFOREM uses COMBIC to predict transmissivity through obscurant clouds, which have been produced by simulated combat events. When activated, COMBIC is employed throughout the gaming exercise, but the smoke effectiveness assessments are limited to discrete engagement segments and only affect certain operations, such as laser range finding and missile flyout. During laser operations, CASTFOREM does consider the affect of obscurants on a laser beam and will attenuate the returning signal appropriately. During guided missile flyouts, CASTFOREM periodically uses COMBIC to determine if obscurants have cause the missile to break lock.

Obscurant usage places a large computational burden on CASTFOREM and can significantly increase run times. Because COMBIC is used in its native form, CASTFOREM can only use standard sources. And, because there is no direct linkage to operational entities, such as vehicles, artillery units, and aircraft, smoke events must be manually inserted by exercise controllers.

6. VIRTUAL SIMULATIONS

In recent years, DoD has invested heavily in distributed interactive simulation (DIS) technologies that enable manned and unmanned simulators to interact on a common virtual battlefield. DIS simulations have been used extensively for small unit training and are increasingly used in other applications, including simulation based acquisition. Interactions are facilitated through the exchange of messages using well defined protocols. The DIS standard provides for the transmission of some smoke information, enabling one battlefield entity to produce a smoke event and report its state to all other networked simulations.

The Modular Semi-Automated Forces (ModSAF) program is used extensively in DIS applications to populate the virtual world with battlefield entities, such as aircraft and armored vehicles. These entities behave in an intelligent manner and are indistinguishable from their manned counterparts.

The use of smoke and obscurants by ModSAF entities is notional. Certain vehicle types have a limited ability to launch salvos of self-protective grenades and artillery/mortar projectiles. No other smoke sources are supported. ModSAF uses pre-computed COMBIC history files to instantiate obscurant clouds, but these clouds are limited to one subcloud each, which severely restricts their fidelity. ModSAF does consider obscurant effects on entity engagements, but few other DIS applications do. The scene generators on most manned DIS simulators cannot render smoke clouds (with the exception of some trailing effects attached to some entities) and they do not affect crew vision whatsoever.

The Close Combat Tactical Trainer (CCTT) is a family of networked simulations that is used to train armor, cavalry, and mechanized infantry platoons in the performance of collective tasks. CCTT includes manned simulators for numerous combat vehicles and a semi-automated forces program (similar to ModSAF) that can control a wide variety of friendly or opposing units. CCTT uses a variant of the DIS standard protocols to establish and maintain the synthetic environment.

CCTT has an extremely limited capability for simulating smoke events and only supports three obscurant types: hydrochloric acid, red phosphorus, and white phosphorus. Manned CCTT simulators do render smoke clouds using an animation technique that can vary transmittance in accordance with obscurant characteristics. This does affect crew visibility which can influence combat operations. Other obscurant effects are not supported.

7. FUTURE REQUIREMENTS

Smoke and obscurants do affect battlefield sensors and those effects can influence combat operations. It is important for obscurant systems to be reasonably represented in models and simulations so that their influence can be properly assessed. The capabilities and limitations of U.S., allied, and opposing forces must all be considered. Smoke and obscurant modeling should not be done for its own sake, but it must be done to insure that soldiers are properly trained and equipped to operate on the dirty battlefield. It is incumbent upon the smoke and obscurant community to make sure that occurs.

The survey presented above describes the current state of smoke and obscurant modeling. It is by no means comprehensive, but does highlight strengths and weaknesses in several application domains. The survey illustrates that smoke and obscurant modelers have done extremely good work where it was feasible to do so. They have developed excellent physical models that reasonably simulate the growth, transport, and diffusion of obscurant clouds while striking a balance between fidelity requirements and computational constraints. And, the physical models have been used in numerous applications to perform useful training and analytical functions. The survey also illustrates, however, that smoke and obscurant modelers have failed to accomplish what heretofore was infeasible to do. Despite all good intentions and a lot of intense effort, they have not managed to insert a significant amount of smoke and obscurant play into the tactical simulations that are routinely used for training and simulation-based acquisition. Given technological limitations, it was just too difficult to achieve. That situation is changing.

Recent advancements in hardware and software technologies are enabling simulations to model physical phenomena with increasing fidelity. The emergence of new design methodologies are facilitating the development of true software components that can readily be used in diverse computing environments. This is an excellent time to begin the development of smoke and obscurant components for the simulation community at large.

These components must be comprehensive, flexible, authoritative, efficient, self-contained, and HLA compliant, as described below:

Comprehensive. Collectively, the simulation components should model all smoke and obscurant systems that U.S. forces are likely to use or encounter on any future battlefield.

Flexible. For maximum applicability across all M&S domains, each component (or variation thereof) must be able to operate at several resolutions. High fidelity simulations will need high fidelity smoke representations while low fidelity simulations will need the opposite. Also, cloud behavior must be 4-dimensional (i.e., sensitive to spatial and temporal variations in atmospheric conditions, if they exist).

Authoritative. Each component must simulate the item it represents with sufficient fidelity to satisfy the smoke and obscurant community at all possible resolutions.

Efficient. Smoke and obscurant modeling is computationally intensive and that burden has limited its utility in many applications. The simulation components must employ more efficient algorithms than those used today, particularly for modeling cloud behavior and obscurant effects. The use of neural nets and related technologies should be investigated to determine if they can enhance performance without degrading fidelity. Also, data exchange requirements among networked simulators must be minimized

Self-contained. Developers will not use the components if it is difficult to integrate them into applications. Consequently, they must be designed using accepted object-oriented

techniques which require they encapsulate all characteristics and behaviors and expose a well-defined interface.

HLA compliant. The simulation components must be developed in accordance with the HLA specification. They must be fully documented with federation object models (FOM) and/or simulation object models (SOM), as appropriate. The components must employ the simulation support services provided by the RTI.

8. REFERENCES

1. Defense Modeling and Simulation Office, 1995: HLA Management Plan: High Level Architecture for Modeling and Simulation, Version 1.6. Defense Modeling and Simulation Office, Alexandria, Virginia.
2. Shirkey, R.C., L.D. Duncan, and F.E. Niles, 1987: EOSAEL 87, Volume 1, Executive Summary. U.S. Army Laboratory Command, Atmospheric Sciences Laboratory, TR-0221-1, White Sands Missile Range, New Mexico.
3. Mason, J.B. and R.G. Steinhoff, 1987: EOSAEL 87, Volume 2, Executive User's Guide. U.S. Army Laboratory Command, Atmospheric Sciences Laboratory, TR-0221-2, White Sands Missile Range, New Mexico.
4. Davis, R.E. and R.A. Sutherland, 1987: EOSAEL 87, Volume 14, Self-Screening Applications Module GRNADE. U.S. Army Laboratory Command, Atmospheric Sciences Laboratory, TR-0221-14, White Sands Missile Range, New Mexico.
5. Hoock, D.W., R.A. Sutherland, and D. Clayton, 1987: EOSAEL 87, Volume 11, Combined Obscuration Model for Battlefield-Induced Contaminants (COMBIC). U.S. Army Laboratory Command, Atmospheric Sciences Laboratory, TR-0221-11, White Sands Missile Range, New Mexico.
6. Ayres, S.D. and S. DeSutter, 1993: Combined Obscuration Model for Battlefield Induced Contaminants (COMBIC92) User's Guide (Draft). U.S. Army Research Laboratory, Battlefield Environment Directorate, White Sands Missile Range, New Mexico.
7. Maynard, H.W., D.W. Hoock, F.W. Hansen, T. Henmi, J.P. Cruncleton, and W.D. Ohmstede, 1987: EOSAEL 87, Volume 12, Simulation of Aerosol Behavior in Realistic Environments (SABRE). U.S. Army Laboratory Command, Atmospheric Sciences, TR-0221-12, White Sands Missile Range, New Mexico.
8. Pennsyle, R.O. and F.J. Wysocki, 1998: Transport, Diffusion, and Radiance (TDR) Version 4.0 Users Manual. OptiMetrics, Inc. for the U.S. Army Edgewood Research Development and Engineering Center, Naval Surface Warfare Center, and Joint Program Office for Special Technology Countermeasures, OMI-639, Forest Hill, Maryland.
9. Pennsyle, R.O., 1996: Droplet Evaporation in Oil Smokes. Proceeding of the Smoke/Obscurant Symposium XIX, Laurel, Maryland.
10. Johnston, D.J. and W.G. Rouse, 1999: The Smoke System Performance Model and Cloud Density Visualization Utility Version 2.0. OptiMetrics Inc. for the U.S. Army Edgewood Chemical Biolgical Center and the U.S. Army Program Manager for Smoke and Obscurants, OMI-653, Forest Hill, Maryland.
11. Horton, W.D. and J.A. Seton, 1999. Hit Avoidance Analysis, Test, and Combat Effectiveness Assessment, Draft Final Report. OptiMetrics Inc. for the U.S. Army Research Laboratory and the Office of the Test Director, Precision Guided Weapons Countermeasures Test and Evaluation Directorate, OMI-640, Las Cruces, New Mexico.

Improved Fidelity for Calculating
Attenuation Through Obscurants

By
Scarlett D. Ayres
U.S. Army Research Laboratory
Survivability Lethality Analysis Directorate
White Sands Missile Range, NM 88002
505-678-4350, **Error! Bookmark not defined.**

Abstract

Assessing the impact of obscurants on performance is a very complex issue. Atmospheric propagation through obscurants can effect acquisition by the U.S. missiles. This report describes a technique, as well as models used to simulate and analyze battlefield scenes in the wavelength of interest using the Combined Obscuration Model for Battlefield Induced Contaminants (COMBIC) model. Most analysis of obscurant effects on battlefield sensors have focused on using a single band-averaged mass extinction coefficient to represent the obscurant's ability to degrade the Line of Sight (LOS). This mass extinction coefficient when combined with the Concentration Length (CL) yields a single number for the transmittance over the wavelength band. The extinction for several wavelength bands are modeled in COMBIC. Project managers have expressed an interest in the spectral attenuation (the variation of the attenuation due to variation in the mass extinction coefficient sometimes referred to as "complex" attenuation by the user) over the band-pass specific to their sensor. An aerosol code has been used to model the variation of mass extinction coefficient with wavelength. The COMBIC CL data can then be combined with the wavelength-dependent extinction coefficient to determine the spectral attenuation over the specific band-pass for the sensor. This represents a significant improvement in the use of COMBIC over using a single number for attenuation to represent a "canned band-pass". The spectral attenuation is used in this report to describe the variation in apparent emissivities for some naturally occurring materials. Analysis shows that the range of the transmitted emissivity for a tree leaf at 8 – 14 microns through White Phosphorus smoke at moderate CL values is .28. The range in emissivity for tree leaf without smoke is .02. The aerosol code is used to compare the band-averaged WP mass extinction coefficient with COMBIC values. Excellent agreement is obtained with a root-mean-square of less than 7% for the visual and 1.54 microns. Therefore, the aerosol code is used to compute the coefficients for the extinction equation used by COMBIC to compute variation of extinction with relative humidity for at .3 microns and 1.54 microns.

1. Introduction

The Broadband Integrated Transmittances (BITS) model was developed by the (then) U.S. Army Atmospheric Sciences Laboratory to numerically calculate broadband transmittances (Davis et al, 1990). This model is located in the Electro-Optical Atmospheric Effects Library (EOSAEL). The BITS model includes spectral effects of the atmosphere, detectors, filters, optical surface, targets, and obscurants on broadband transmittances. The BITS model allows the user to input the spectral response of the detector and filters into the model as spectral response-wavelength pairs. However, most project managers of target acquisition systems, have their own in-house system performance model. SLAD has been requested by the Stinger project office to provide spectral attenuation for use in just such a model. An

option to access a file containing the variation in extinction to compute the spectral attenuation over a band-pass specified by the user has been added to the model.

Davis, Berrick and Gillespie in 1990, performed a comparative study between the Beer's law calculation and band-integrated calculations of WP smoke for ASL SMART transmissometer using the BITS model. To simplify the analysis, the target spectral signature and the system optics were assumed to be wavelength independent and have been set to unity. They found that large differences between predicted transmittances using an averaged extinction coefficient when compared to spectral extinction can occur. These differences for the conditions modeled can be important below transmittance of .1, the range in which threshold of detection becomes critical for most sensors.

Sutherland, Yee, Fernandez and Millard also made a comparison study in 1996 for various types of fog. They modeled the mass extinction coefficient as a constant mean component and a wavelength dependent component. The received signal can be considered as being composed of a wavelength independent part multiplied by a correction factor. They found that the correction factor is nearly one for advective fog where the mass extinction coefficient is nearly independent of wavelength. For other types of fog like artificial fog and radiative, there is increasing departure of the correction factor from one with increasing CL. Though, the correction factor can be ignored except for very high CL values.

It is convenient to also use a band-averaged emissivity to describe the background for infrared scenarios. The emissivity is defined as the ratio of radiant emittance of the surface to the radiant emittance of a blackbody at the same temperature. Most IR scene generation models use band-averaged emissivities. For some backgrounds, the emissivity is nearly constant. However, other backgrounds exhibit some variation in the emissivity with wavelength. The addition of an obscurant that exhibits variation in extinction over the wavelength band causes the apparent emissivity to vary further. This reports shows how the apparent emissivities for several backgrounds vary in the presence of White Phosphorus for different CLs.

With the recent emergence of the eyesafe laser, the Combined Arms Strategic Task Force Evaluation Model (CASTFOREM) needed the capability to model obscuration effects on these sensors. Phosphorus-based smokes are found in most country's inventory. CASTFOREM models these smokes using the COMBIC model. However, the default tables in COMBIC do not contain extinction at 1.54 microns for WP. The effectiveness of these smokes is dependent on the ambient relative humidity. COMBIC uses a fourth-order extinction equation to compute the extinction. The coefficients of this equation are dependent upon the wavelength and the type of smoke. The Aerosol-Hygroscopic code was used to help determine these coefficients. These coefficients are also determined for the ultraviolet (UV) wavelengths of .3 microns. Several systems such as Stinger use a UV sensor in addition to another wavelength to help discriminate targets from false targets. The Aerosol-Hygroscopic code is used partly because a dearth of actual measured extinction data for WP at 1.54 microns and UV wavelengths exists.

2. Models

2.1 COMBIC

The COMBIC computer simulation predicts spatial and temporal variation in transmission produced by various munitions and vehicles. COMBIC models the effects of reduction in electromagnetic energy

(visible through infrared (IR) wavelengths) by combining the munition characteristics with meteorological information of an idealized real world. It produces transmission histories at any of seven wavelength bands for a potentially unlimited number of sources and lines of sight (LOS. The extinctions for the seven wavelengths for twenty obscurants are included in the model. COMBIC also has the capability of modeling the variation of extinction with wavelength for hygroscopic smokes like WP (Ayres and DeSutter, 1993). Path-integrated concentration is determined for each observer (seeker)-target pair, and transmittance are computed at each of seven wavelength bands for (in principle) any scenario which is defined by multiple sources and active LOS.

2.2 Aerosol-Hygroscopic Code

The mass extinction coefficient is a wavelength-dependent optical property of the obscurant material. It can also depend on the particle size distribution, particle composition, refractive indices, shape and orientation. Most established smokes in the US inventory and modeled by COMBIC's default tables are considered to be spherical. The mass extinction coefficients for many smokes in these default tables are heavily weighted towards measurements rather than theory. COMBIC uses the extinction per unit obscurant concentration integrated over the entire size distribution of airborne particles. The model also uses a band-averaged mass extinction coefficient for wavelength bands .4 - .7 microns, .7 - 1.2 microns, 3- 5 microns, and 8 - 12 microns. The extinction coefficient in COMBIC accounts for scattering of radiation out of the path of propagation and absorption of radiation along the path of propagation.

White Phosphorus and Red Phosphorus burn to produce a hygroscopic smoke containing phosphoric acids. The extinction for these smokes is primarily due to scattering in the visible and absorption in the infrared (IR). These smokes are composed of spherical liquid particles that grow with relative humidity to an equilibrium size by absorbing ambient moisture that depends on the ambient relative humidity. The mass extinction varies significantly with relative humidity. Theory is needed to supplement measurements to compute the extinction variation for the various wavelengths over all relative humidities. Extinction of airborne aerosol (m**2/g) depends on four factors: (1) the index of refraction of the obscurant; (2) the distribution of particle sizes; (3) shape and orientation of particles; and for hygroscopic smokes; (4) the effect of dilution by water absorbed from the air on mass, size distribution and effective refractive index (Hoock and Sutherland, 1993). White Phosphorus smoke can be modeled as spheres allowing the use of the Mie theory.

The Mie theory provides exact computation of absorption, scattering and extinction coefficients for an individual, homogeneous sphere based upon the particle radius, mass density and refractive index. The problem is that most aerosols have particles that range is size. Choosing an appropriate size distribution can effect results. Furthermore, hygroscopic smoke particle size distribution and indices of refraction change concurrently with relative humidity. The difficulty is to compute the extinction of the composite smoke particle. The Aerosol-Hygroscopic Code produced by Klett and Sutherland, 1988, is based upon the Mie theory and utilizes a lognormal particle distribution. The geometric mean radius and the geometric mean standard deviation σ characterize this distribution. The model uses the refractive indices for water and WP, combined with lognormal particle size distribution dependent upon relative humidity to compute the mass extinction coefficients vs. wavelength for any desired relative humidity. Though the refractive indices for water are well known, the indices for the composite smoke particle must be modeled with mixing rules. The Aerosol-Hygroscopic model uses the rule of volumetric additivity of dielectric constants (Newton's rule) as the mixing rule.

Figure 1 shows the mass extinction coefficient for various relative humidities using Kletts and Sutherland's (1988) Aerosol-Hygroscopic Code. The mass extinction coefficient in the visible region actually decreases at high relative humidities. This is due to the particle size distribution shift to larger radii with the absorption of moisture and the resultant decrease in refractive index. Water vapor is the strongest absorber for clear air in the 8 – 12 microns. Klett and Sutherland found that vapor depletion in the aerosol could be ignored except for high CL. Note, that the refractive indices for WP peak in the 8 - 12 microns wavelength band. The Aerosol-Hygroscopic Code is used in this effort to compute the extinction at .3 and 1.54 microns and to compute the spectral extinction coefficient.

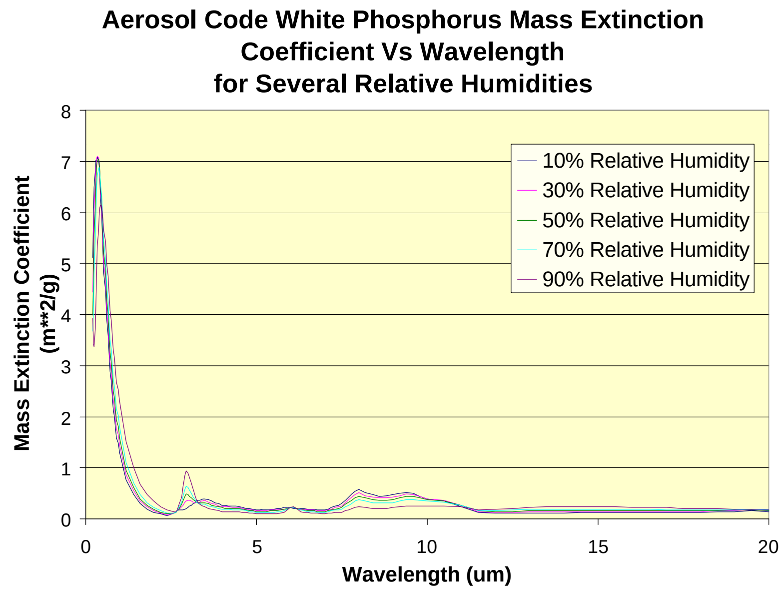


Figure 1 The variation of the White Phosphorus mass extinction coefficient vs wavelen shown for 10%, 30%, 50%, 70% and 90 relative humidities

3. Near IR (1.54 um)

Laser rangefinders measure the time-of-flight of a short pulse of laser light to and from a target. This time of flight is then converted to a range, which is displayed in the rangefinder's sighting optics. Most laser rangefinders are not eyesafe. This limits their use in training and provides safety concerns in the field. Many of these lasers emit a wavelength of 1.064 microns. While invisible to the human eye, this wavelength is not only passed through the eye to the retina, but is also focused by the eye's lens onto the retina. At 1.064, microns the maximum permissible exposure for single pulse lasers is limited to a few microjoules of energy. Hence at the nominal 15mJ operating output levels of some lasers, the potential for eye damage is quite high (Galoff and Sliney, 1990). Neutral density filters were developed that reduced the eye hazard of these lasers but the operational usage of the 1.06-micron lasers was also reduced.

Beyond 1.4 microns, the eye no longer focuses laser energy on the retina and higher energy levels can be tolerated. Several types of lasers were studied that operated at different wavelengths, but the Army eventually settled on a 1.54 micron laser that was eyesafe at the aperture, even when viewed with magnifying optics. Full scale production of the Mini Eyesafe Laser Infrared Observation Set (MELIOS) has started. An unintentional benefit of switching from the 1.06 micron laser to the 1.54 micron laser is that the extinction is significantly reduced. A quick inspection of figure 1 shows that the extinction curve

is quite steep in the near-IR. Assuming that the WP mass extinction coefficient for the 1.54 wavelength and the 1.06 wavelength is the same would introduce errors up to 200% in computing optical depth. In order to compute the 1.54 micron mass extinction coefficient, the Aerosol-Hygroscopic Code was run with varying geometric mean radius and standard deviation σ for 1.06 microns until the best fit with COMBIC produced mass extinction coefficients was obtained.

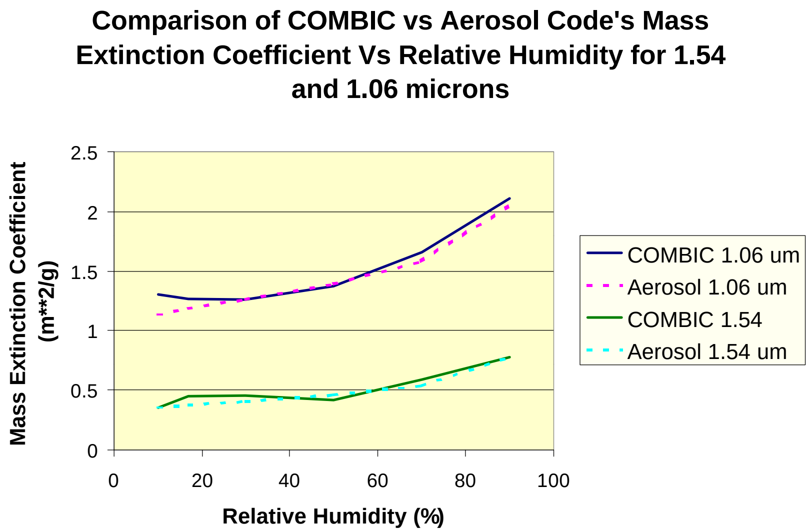


Figure 3 White Phosphorus Mass extinction coefficient vs. relative humidity and 1.54 microns computed by COMBIC and the Aerosol-Hygroscopic Code

COMBIC computes the mass extinction coefficient through the following empirical equation:

$$a(l) = a_1 * RH + a_2 * RH^2 + a_3 * RH^3 + a_4 * RH^4$$

where α(λ) is the mass extinction coefficient for wavelength or wavelength band and RH is the relative humidity. Curve fitting the 1.54 micron data produced by the Aerosol-Hygroscopic Code yields a_1 = 5.2782E-02, a_2 = -2.0106E-03, a_3 = 2.9326E-05, and a_4 = -1.3817E-07. The correlation coefficient is .962 proving that the derived curve for COMBIC strongly matches the data produced by the Aerosol-Hygroscopic model. Figure 2 shows the mass extinction coefficient vs. relative humidity computed by COMBIC's empirical extinction equation for 1.06 and 1.54 microns and by the Aerosol-Hygroscopic code for 1.06 microns and 1.54 um. Geometric mean radius and sigma used by the Aerosol-Hygroscopic code is r =. 215 microns and σ =1.2 microns. Note that the agreement between COMBIC and the Aerosol-Hygroscopic code at 1.06 microns is quite good with a root-mean-square (rms) deviation of 2.85%. Thus, there is a large degree of consistency between COMBIC and the Aerosol-Hygroscopic Code.

4. UV Extinction

Currently, COMBIC contains in its default tables, extinction data from visible to far IR. However, some sensors operate in the ultraviolet (UV). Also, UV emissions are considered a missile observable. UV extinction for some non-hygroscopic smokes have been collected elsewhere (Johnston and Rouse 1997).

The coefficients for the extinction equation used by COMBIC is needed for hygroscopic smokes. The same methodology used in computing the coefficients for COMBIC's empirical extinction equation at 1.54 microns is used here. However, the Aerosol-Hygroscopic model is run to compute the mean geometric radius and standard deviation that gives a best match with COMBIC at visual wavelengths. These values are then used in the Aerosol-Hygroscopic model to compute the extinction at .3 microns. Figure 3 shows the mass extinction coefficient vs. relative humidity for .4 - .7 microns and .3 microns produced by the Aerosol-Hygroscopic model and by COMBIC's extinction equation for WP. The geometric radius is .215 microns and geometric standard deviation σ is 1.5 microns. The rms percent difference between the two models for the visual waveband is 6.8. The coefficients for the extinction equation used by COMBIC at UV wavelengths become a_1 = 5.2782E-02, a_2 = -2.0106E-03, a_3 = 2.9326E-05, and a_4 = -1.3817E-07. A zeroth-order term, a_0 = 3.3420 had to be added in order to obtain the best fit. The correlation coefficient is .997 proving that the derived curve for COMBIC strongly matches the data produced by the Aerosol-Hygroscopic model.

Note that the agreement between COMBIC's extinction equation and the Aerosol-Hygroscopic model for visual wavelengths is fairly good for humidities above 30%. There is increasing discrepancy below 30% relative humidity. One possible source for this discrepancy could be that the indices of refraction for dry WP particulate were extrapolated from "wet" indices. However, the extinction at visual wavelength for WP is believed to be insensitive to the indices. Another possible source of discrepancy is that the extinction at visual wavelengths is *very* sensitive to the particle size distribution. Figure 1 shows the extinction exhibits a marked peak at visual wavelengths. Changing the geometric mean radius or sigma even slightly can have significant effects on the extinction. The values computed by here are believed to be well within the noise of real world values.

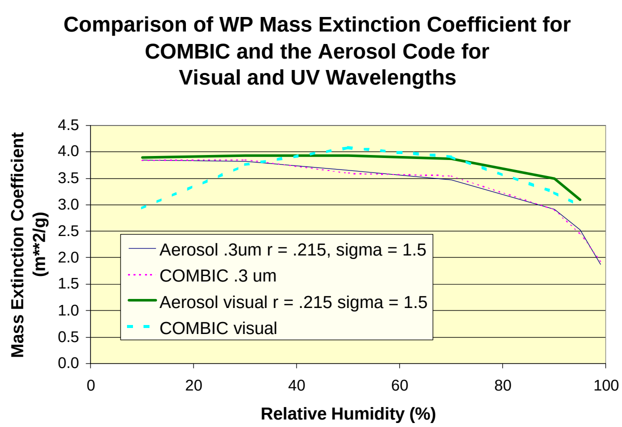


Figure 4 Comparison of WP mass extinction coefficient for COMBIC and the Aerosol Code for visual and UV wavelengths.

5. Spectral Emissivities of Some Natural Soils and Vegetation

The variation of the mass extinction coefficient can effect the natural emissivity. Figures 4-7 shows the emissivity of red clay, fine sand, coarse sand and a tree leaf for the 8-14 um region (Sutherland, 1986) for clear air (top curve) and for increasing WP CL values. These figures show that the spectral attenuation of WP in this wavelength region adds a spectral dependency to the emissivity that may not be present in clear air. The reason for this variation is that the refractive indices of phosphoric acid droplets vary the

most with relative humidity in the 8 – 12 micron wavelength band (Hoock and Sutherland, 1993). The emissivity for tree leaf was nearly constant over the wavelength band in clear air. For increasing CL values, the figures show that there is an increasing wavelength dependence of the apparent emissivity of a tree leaf for this wavelength region. This is also true for clay and fine sand. The effects of smoke on coarse sand is somewhat different. At increasingly higher CL values the smoke degraded some of the natural variation in emissivity.

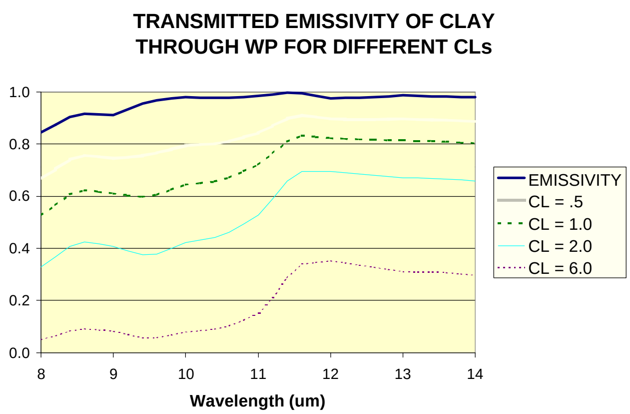


Figure 4 Emissivity for red clay for 8 - 14 microns

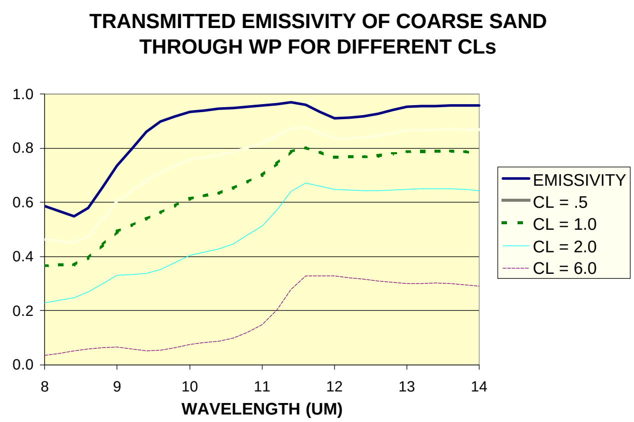


Figure 5 Emissivity for coarse sand for 8 - 14 microns

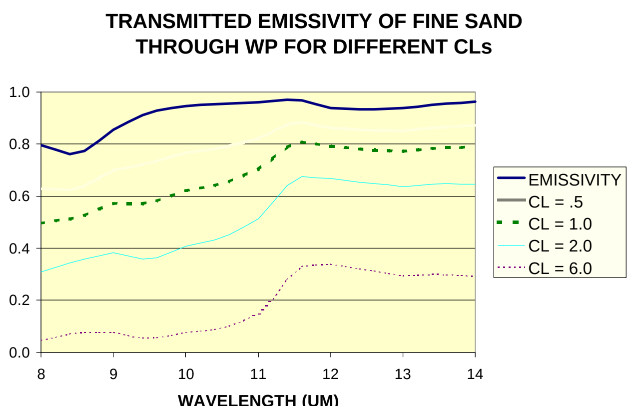


Figure 6 Emissivity for fine sand for 8-14 um

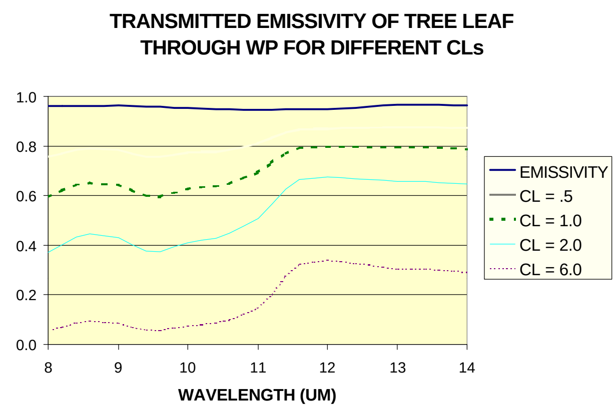


Figure 7 Emissivity for tree leaf for 8 – 14 microns

6. Conclusion and Future Work

Analysis of the WP mass extinction coefficient computed by the Aerosol-Hygroscopic code shows that it compares very favorably with the extinction coefficient computed by COMBIC at .4 - .7 microns and 1.54 microns. Therefore, the code can be used with confidence to compute the mass extinction coefficient variation with relative humidity at .3 microns and 1.54 microns. The data is curve fitted for each wavelength using a fourth order polynomial for eventual inclusion in COMBIC extinction module for use by CASTFOREM. The correlation coefficient is quite high (> .95) between the Aerosol-Hygroscopic code data and the fourth order equation used by COMBIC.

The effect of smoke on natural emissivities is complex. The spectral variation of the backgrounds examined in this report increased with increasing CL except for coarse sand. The effect of smoke on coarse sand is to “wash out” some of the natural variation in spectral emissivity. Analysis shows that the range of the transmitted emissivity for coarse sand at 8 – 14 microns through WP smoke at moderate CL values of 6 g/m^2 is .29. The range in emissivity for coarse sand without smoke is .42.

Future work will include:

- Acquiring data for validation of coefficients of extinction equation for .3 and 1.54 microns
- Add extinction for .3 microns and 1.54 microns to the default tables (CASTFOREM)
- Using COMBIC and the hygroscopic code to compute the spectral attenuation over the bandpass for STINGER.
- Inclusion of sensor effects and aerosol emissivity (Nealon and Sutherland, 1999)

7. References

Ayres, S.D., and S. DeSutter, 1993: “Combined Obscuration Model for Battlefield Induced Contaminants (COMBIC) Users Guide,” U.S. Army Research Laboratory.

R. E. Davis, S. E. Berrick and P.S. Gillespie; 1990, “Broad-Band Integrated Transmittances: The Bits Module,” Proceedings of the Eleventh Annual EOSAEL/TWI Conference, U.S. Army Atmospheric Sciences Laboratory, White Sands Missile Range, New Mexico.

Galoff, P. K and D.H. Sliney, 1990: “Laser Safety, Eyesafe Laser Systems, and Laser Eye Protection,” Proceedings for the International Society of Optical Engineering, Vol. **1207**, 112-123, P.O. Box 10, Bellingham, Washington, 98277-0100.

Holst, G. C., 1995: “Electro-Optical Imaging System Performance,” JCD Publishing, 2932 Cove Trail, Winter Park, FL 32789.

Johnston, D. J., W.G. Rouse 1997: “The Vehicle Smoke Protection Model and Cloud Density Visualization Utility, Version 1.1,” OMI-598, 1 Newport Drive, Suite H, Forest Hill, MD 21050.

Hoock, D. W., and R. A. Sutherland, 1993: “Chapter 6 – Obscuration Countermeasures,” The Infrared & Electro-Optical Systems Handbook, Volume 7- Countermeasures, Editor - D. H. Pollock, Environmental Research Institute of Michigan, Ann Arbor Michigan.

Sutherland, R.A., 1986: “Broadband and Spectral Emissivities (2-12 μm) of Some Natural Soils and Vegetation,” Journal of Atmospheric and Oceanic Technology, Volume 3, No. 1.

Sutherland, R.A., 1988: “Effects of Atmospheric Moisture in Determining Obscurant Optical Properties from Field Data,” Ninth Annual EOSAEL/TWI Conference, Atmospheric Sciences Laboratory, White Sands Missile Range, NM 88002.

Sutherland, R.A., Y. P. Yee, G. L. Fernandez, and J.B. Millard, 1996: “Droplet size and transmittance spectra of mechanically generated water fogs,” Atmospheric Research 41: 299-319.

J.F. Nealon and R.A. Sutherland, 1999: “Cloud Contrast Modeling and Validation for Targets”, 5th Annual JAWS Symposium & Exhibition, San Diego, CA, 14 –18 June, 1999. In Press.

Silent Sentry™
Passive Surveillance

Lockheed Martin Mission Systems

Jonathan Baniak
Dr. Gregory Baker
Ann Marie Cunningham
Lorraine Martin

June 7, 1999

Contact: Lorraine Martin
Telephone: (301) 240-5658

1 Introduction

Silent Sentry™ 2 (SS2) is Lockheed Martin's new all-weather, passive surveillance technology. The SS2 system is a receive system that exploits transmissions from multiple commercial FM radio stations to passively detect and track airborne targets in real-time. On 10 May 1999, Silent Sentry received *Aviation Week & Space Technology* magazine's Technology Innovation Award, which recognizes innovative product and service technologies in the global aerospace business.

Last year, Lockheed Martin Mission Systems publicly announced the Silent Sentry system. Since then, the development team has migrated the technology to a prototype, mobile platform and validated the system's surveillance accuracy during a recent military exercise held to evaluate current and emerging technologies. The March 1999 All Services Combat Identification and Evaluation Team (ASCIET) Joint Services Exercise at Ft. Stewart, Georgia provided the team an opportunity for real-time testing of Silent Sentry against a variety of aircraft, including fighter, bomber and radar surveillance aircraft and helicopters.

The heart of Silent Sentry is its innovative Passive Coherent Location (PCL) technology developed by Lockheed Martin Mission Systems, which uses everyday broadcast signals, such as those for television and radio, to illuminate, detect and track objects. A passive detection system for U.S. government civil agency and military purposes, Silent Sentry transmits no radio frequency (RF) energy as conventional radar does and has no RF "signature" to alert enemy threats. Instead, it can use the energy that already exists in airspace for detection purposes, and does not adversely affect or harm the environment.

By using broadcast transmitters and signals available throughout the world, Silent Sentry:

- assists in casting a "wider net" when used in conjunction with existing surveillance systems,
- provides new levels of early detection, to reveal tangible proof of activity, and
- enables rapid, defensive reaction to threats.

The system can be deployed to fill gaps in existing radar coverage and enhance global awareness and command-control decision-making.

Silent Sentry is a multi-static illuminator surveillance system (i.e., receiver and transmitters are not co-located) which determines precise three-dimensional target trajectories, and unlike "scanning" radars, Silent Sentry provides continuous coverage of the airspace. The Silent Sentry configurations include versions which can be mounted in buildings and fixed structures, or in deployed configurations, such as trucks, or shelters, for rapid relocation.

Recent advances in commercial technology, such as high-speed processors and high dynamic-range receivers, help make Silent Sentry a low-cost approach to effective and reliable real-time surveillance against a wide range of potential threats. A typically configured system includes Silicon Graphics, Inc.® processors, the Autometric Edge Product Family™ visualization and analysis software, and receivers built by Lockheed Martin from commercial products.[1]

---

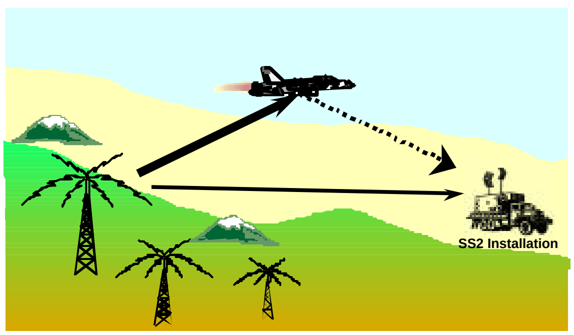
[1] Silent Sentry is a trademark of the Lockheed Martin Corporation.
Silicon Graphics is a registered trademark of Silicon Graphics, Inc.
Autometric Edge Product Family is a trademark of Autometric, Inc.

•

2 What is Silent Sentry™? (An Overview)

2.1 SS2 Basic Concept and Features

SS2's continuous wave (CW) multistatic technology provides an all-weather, passive surveillance capability through the exploitation of radiant energy from commercial FM radio stations. The transmitted signals from these illuminators are scattered from airborne targets and received by the SS2 target antenna (a horizontal linear phased array antenna in the current implementation). Separate, reference antennas also receive the direct path signals from the FM transmitters. High dynamic-range receivers are used to accommodate the dynamic range requirements for receiving direct and scattered signals simultaneously.



Basic Concept of Silent Sentry Operation

Continuous coverage of 90 degrees azimuth is achieved through the use of innovative digital signal processing algorithms. Delay (time difference of arrival) and Doppler (frequency difference of arrival) measurements for each detected target are extracted. The measurement data are associated by target and a tracking filter estimates the state vector (position, velocity, and acceleration) for each target. This state data can then be presented to a tactical display or communicated to other systems via standard data-links.

In the current version of SS2, coarse 2-D tracking solutions are possible when the target is detected using a single illuminator. Good 2-D solutions are feasible whenever the target is detected on two or more geometrically

diverse FM illuminators. Tracking solutions in 3-D are feasible when the target is detected on three geometrically diverse FM illuminators.

The system can provide short latencies since it is a staring, not a scanning, system. (Recall that traditional radar uses pulsed signals, in part due to their monostatic design.) The FM illumination continuously saturates the coverage region and SS2, with its staring beams spanning the coverage region and high update rate, enabling early target detection. The use of commercial broadcast transmitters provides excellent low altitude illumination of targets, which, when combined with favorable receiver siting, provides low altitude surveillance.

2.2 System Description

Silent Sentry System Description

Silent Sentry is a single receive system composed primarily of the following components the majority of which are commercial off-the-shelf (COTS):

- **Target array** – a linear phased array for detecting the scattered energy from targets in the region of interest

- **Reference antennas** – single elements, identical to those in the target array, used for reception of the direct path signals from the FM illuminators

- **High Dynamic Range Receivers --** accommodate the dynamic range requirements for receiving direct and scattered signals simultaneously

- **A/D Converters --** the system possesses the capability to record data at this level, which is particularly useful for post-mission analysis

- **Processor** – Silicon Graphics, Inc. (SGI) general purpose processor

- **Displays** – SGI Octane workstation and visualization products from the Autometric Edge Product Family™

- **High Speed Tape System** – a SCSI attached striping tape controller with 5 tape drives

Mission planning and system performance predications are critical for any surveillance system and imperative for line-of-sight systems. Silent Sentry includes a suite of mission planning and system tools that are collectively called the Sensor Performance and Analysis Tools (SPAT). Among these tools are signal simulators, a trajectory simulator, beam formulator, Signal to Noise Ratio (SNR) calculator, and an illuminator database. These tools in combination with several other standard radar modeling tools were utilized in planning and preparation for ASCIET mission at Ft. Stewart in March 1999. The essential functions of SPAT are:

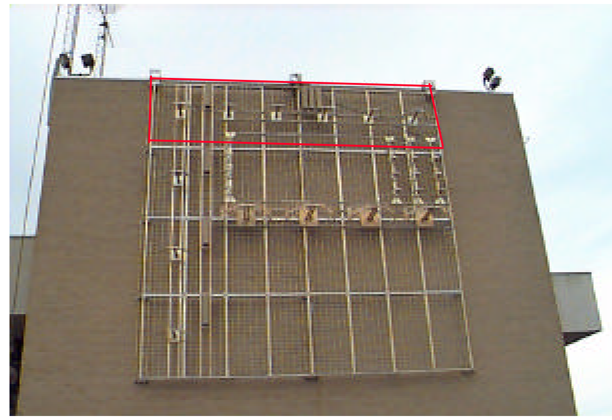
- **Illuminator Selection and Receiver Siting -** analyzes illuminator coverage for various combinations of FM radio stations in combination with the receiver location.

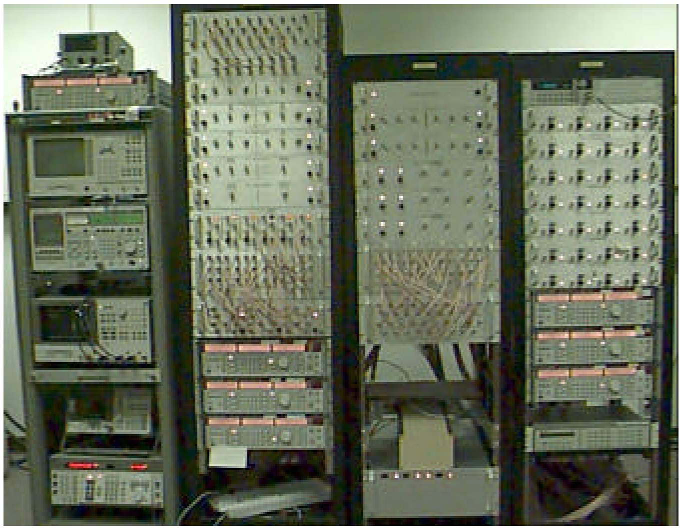
- **Performance Prediction -** for a given site and combination of illuminators and trajectory, determines the probability of detection, the accuracy and SNR values.

2.3 SS2 Configurations

Lockheed Martin currently has two configurations of SS2: the Fixed Site System (FSS) and the Rapid Deployment System (RDS).

The FSS operates in Gaithersburg, MD, runs real-time using a full configuration of processors, and processes all data real-time. The system is designed for flexibility, with many aspects of the system configurable according to desired data processing rate, sampling patterns, performance objectives, and available hardware.





The Fixed Site System: Receivers (left) and Wall-Mounted Antenna Array (right).
The current implementation of SS2 uses only the horizontal array outlined in red.

Reference Antenna

Target Antenna

The Rapid Deployment System

The RDS is used for real-time data collection and real-time data processing. The RDS is currently deployed in a self-sufficient trailer including power and environmental controls. It is contained in a van, with the phased array antenna mounted on the side, and the reference antennas on the top. The ruggedized receivers, processors and control workstation are contained in half the van. The heating system and generator are housed in the other half. The van is a Faraday cage to prevent emissions from the processors from interfering with the antenna reception. This configuration was used at the recent testing event reported above. The van is larger than required for deployed operations, but was an available asset in the Lockheed Martin inventory.

3 Capabilities of Silent Sentry™

- Silent Sentry has some inherent features and unique capabilities that warrant examination.
- **Surveillance for Challenging Targets**
- The ASCIET Joint Services Exercise at Ft. Stewart, Georgia, in March 1999 gave Lockheed Martin an opportunity for real-time testing of its Silent Sentry system against a variety of aircraft, including fighter, bomber and radar surveillance aircraft and helicopters. In past technology experiments, Lockheed Martin has demonstrated nonreal-time and real-time capabilities against a variety of other targets, including helicopters, rockets, ballistic missiles, and re-entry vehicles.
- **Excellent Altitude Coverage**
- Since TV and FM broadcast stations focus energy toward the Earth's surface, they illuminate low flying targets. Multi-illumination not only provides illumination to areas where mountains and valleys may block one illumination source, but the geometric diversity provides additional information from differing viewing aspects of the targets.
- **Inherent Survivability**
- Active radars quickly become combat targets due to their energy emissions. Silent Sentry is a truly passive system, which emits no signal, so it is well suited to passive operation. Silent Sentry is also an "environmentally friendly" sensor since it reuses commercial illumination energy (instead of disrupting the broadcasts with its own strong signals).
- **Effective All Weather Operation**
- Broadcast Signals in the UHF, VHF, and FM bandwidths are virtually immune to weather-induced degradation and operate equally well day and night.
- **Military Operations**
- Since Silent Sentry emits no signals, it can be placed forward on the battlefield without being detected, providing earlier warning of potential threats and expanding the battlespace understanding.
- **Low System Cost**
- Silent Sentry is a phased array system with no rotary mechanical components; in addition, it has no transmission components. These attributes greatly reduce power requirements, mechanical upkeep,

and cost. In addition, the system is primarily composed of COTS products and can be fielded in unmanned configurations.

- **SS2 Design Goals**

- The advertised system performance figures are dependent on several factors; the most important of which are the geometric diversity of the illuminators, the illuminator transmission power, and the Radar Cross Section (RCS) of the target.

Performance of a mid-range system configuration

System Parameter	Value
*Detection Range	220 km
Range Depth Coverage	150 km
Azimuth Coverage	60^o to 360^o
Elevation Coverage	50^o
Target Tracking Update Rate	8 per second
Target Capacity	200+
Power requirements	10 kW
Footprint (excluding antenna)	27 square feet

* Value based upon an RCS=10 m^2 @ 100 MHz, $P_d > 0.95$, FAR < 10^{-3}.

- **Mission Planning Tools**

- There are a significant number of performance prediction and planning tools available as part of Silent Sentry. The mission planning and illuminator selection tools allow for system deployment (or simulation) anywhere in the world based on the FCC and ITU transmitter databases.

4 Conclusion/Forward Plan

The system is intended as a passive detection and tracking system for U.S. government civil agency and military purposes; it can be deployed to address gaps in radar coverage to provide “early warning” detection, and enhance command and control decision-making. The Silent Sentry™ architecture is designed to be expandable and scalable.

The characteristics are:
- Sensitivity to allow range detection of a wide variety of targets
- Exploitation of continuous wave (CW) signals allowing for high update rates
- Complete and continuous airspace coverage (within system parameters)
- Local operations and remote, controlled system access

Silent Sentry™ provides:
- Real-time three dimensional tracking and visualization of airborne targets
- Exploits multiple sources of illumination (i.e., radio and TV broadcast signals and optional cooperative transmitters)
- Comprehensive data recording and playback capabilities
- Extensive simulation and mission planning tools

We believe that Silent Sentry represents the threshold of an exploding new technology. The technology has the potential to revolutionize how various surveillance operations are performed. Recent field exercises have proven viability of the technology and the mission planning toolset. We look forward to

continued research and development, which will lead to addition to the current system of TV signal exploitation, as well as refinement of various processing and tracking algorithms. One of the most exciting features of Silent Sentry that will be explored further is the inherent signal information that can be used for target identification and classification. These advancements in battlespace awareness will provide increased capability and robustness to the warfighter.

For Additional Information:

More information regarding Silent Sentry and its underlying technology can be obtained at this Lockheed Martin website:

Error! Bookmark not defined.

Or by contacting:

Tom Kuba
301-240-6668,
tom.kuba@lmco.com.